The Reconstruction and Failure Analysis of The Space Shuttle Columbia

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Several days following the Columbia accident a team formed and began planning for the reconstruction of Columbia. A hangar at the Kennedy Space Center was selected for this effort due to it's size, available technical workforce and materials science laboratories and access to the vehicle ground processing infrastructure.

The Reconstruction team established processes for receiving, handling, decontamination, tracking, identifying, cleaning and assessment of the debris. Initially, a 2-dimentional reconstruction of the Orbiter outer mold line was developed. As the investigation progressed fixtures which allowed a 3-dimensional reconstruction of the forward portions of the left wing's leading edge was developed.

To support the reconstructions and forensic analyses a Materials and Processes (M&P) team was formed. This M&P team established processes for recording factual observations, debris cleaning, and engineering analysis. Fracture surfaces and thermal effects of selected airframe debris were assessed, and process flows for both nondestructive and destructive sampling and evaluation of debris were developed. The Team also assessed left hand airframe components that were believed to be associated with a structural breach of Columbia. A major portion of this analysis was evaluation of metallic deposits were prevalent on left wing leading edge components.

Extensive evaluation of the visual, metallurgical and chemical nature of the deposits provided conclusions that were consistent with the visual assessments and interpretations of the NASA lead teams and the findings of the Columbia Accident Investigation Board. Analytical data collected by the M&P Team showed that a significant thermal event occurred at the left wing leading edge in the proximity of LH RCC Panels 8-9, and a correlation was formed between the deposits and overheating in these areas to the wing leading edge components. The analysis of deposits also showed exposure to temperatures in excess of 1649°C (3200°F), which would severely degrade support structure, tiles, and RCC panel materials. The integrated failure analysis of wing leading edge debris and deposits strongly supported the hypothesis that a breach occurred at LH RCC Panel 8.

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The Reconstruction and Failure Analysis of The Space Shuttle Columbia

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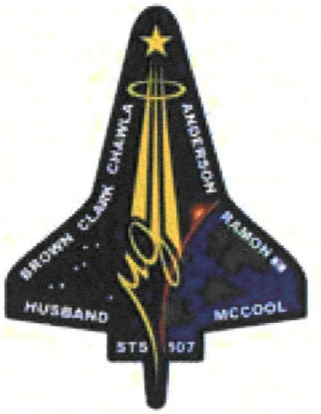

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Jeff Hausken

Stephanie Hopper

Mark Hudson

Dave Lubas

Robert Perez

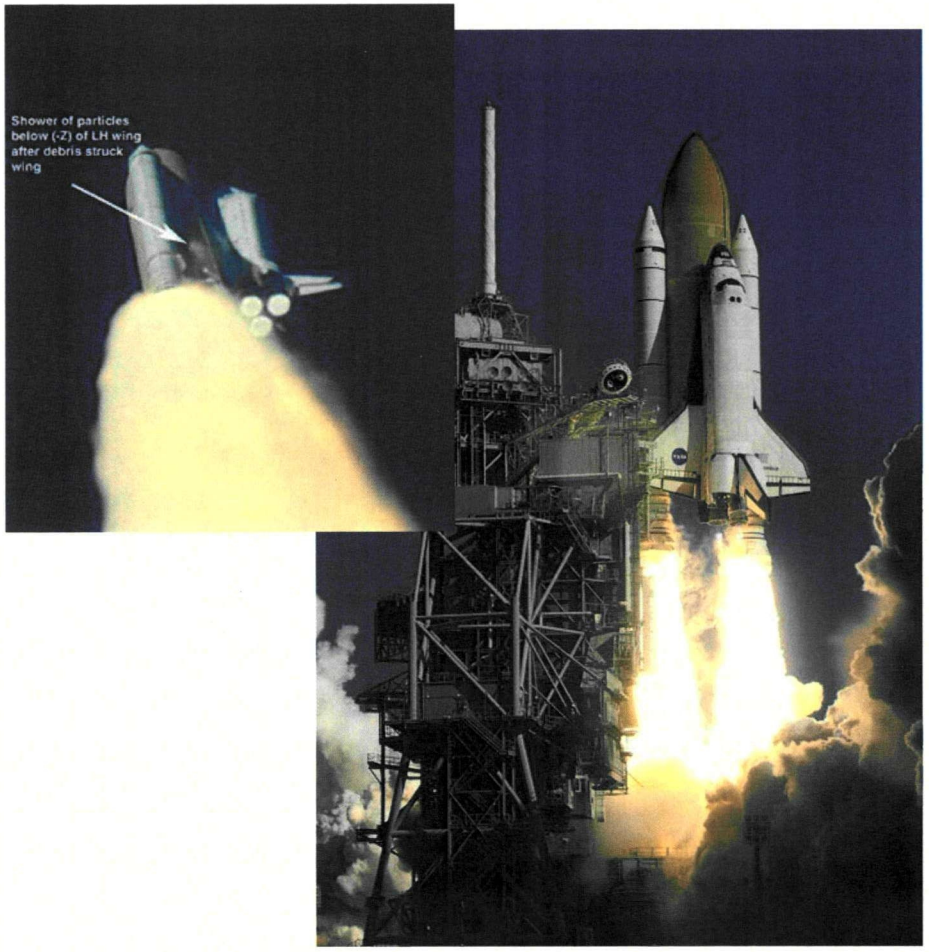
Keith Pope

Janet Ruberto

Marcella Solomon

Jim Stewart

STS-107 Timeline



- Launch – January 23, 2003 at 10:39 AM
- Launch + 81.9 seconds, External Tank left bipod foam strikes Columbia's left wing
- February 1, 2003 8:15:30 am, Commander Husband and Pilot McCool execute de-orbit burn
- Entry interface (approx. 400,000 ft), 8:44:09 am
- Over California first signs of debris shedding observed at 8:53:46 am
- Approximately 1 minute 24 seconds into peak heating region of re-entry interface, 8:52:17, an off-nominal temperature in the left main landing gear brake line sensor
- First sign of trouble reported in mission control, at 8:54:24 when four hydraulic sensors were indicating "off-scale low".
- Loss of signal from Columbia recorded at 8:59:32 am.
- Videos made by observers on the ground at 9:00:18 am revealed that the Orbiter was disintegrating

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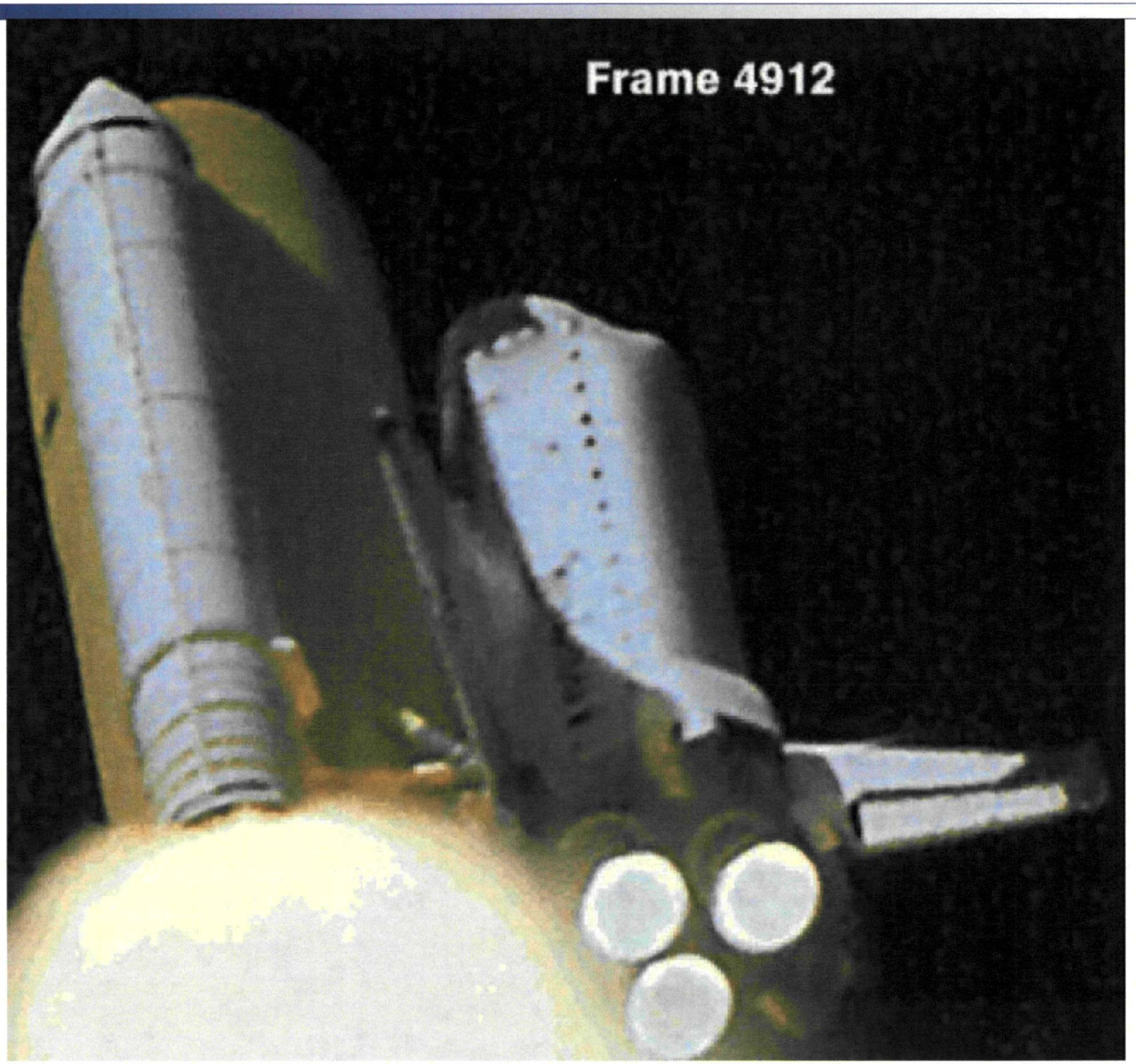
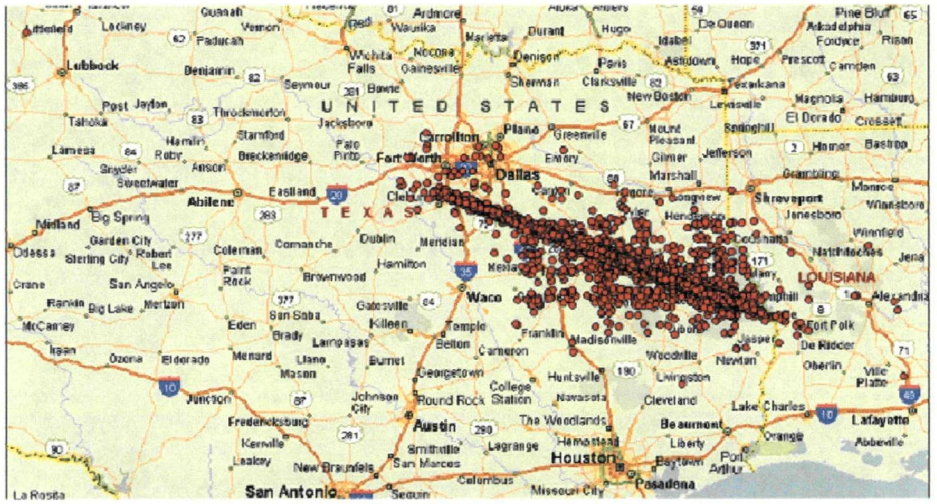
STS-107 Foam Impact

Foam Impact



Recovery

- Columbia was traveling at Mach 18 at an altitude of 208,000 feet at time of break-up
- The size of the debris field was 645 miles long and 10 miles long
- Each piece of debris was photographed, analyzed for potential hazards, given a unique identification
- Each piece's location was noted and a preliminary identification was attempted
- Debris was then sent to one of several stationing locations before being sent to the Kennedy Space Center for reconstruction
- Over 83,900 items were recovered representing an estimated 38% of Columbia by weight



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Reconstruction

- Reconstruction is a common aircraft accident investigation tool used to trace damage patterns and failure clues to aid in the determination of probable cause
- A 2-D Reconstruction plan was developed before the arrival of the debris
- The option for possible 3-D reconstruction was deferred until the amount of debris and initial observations were made

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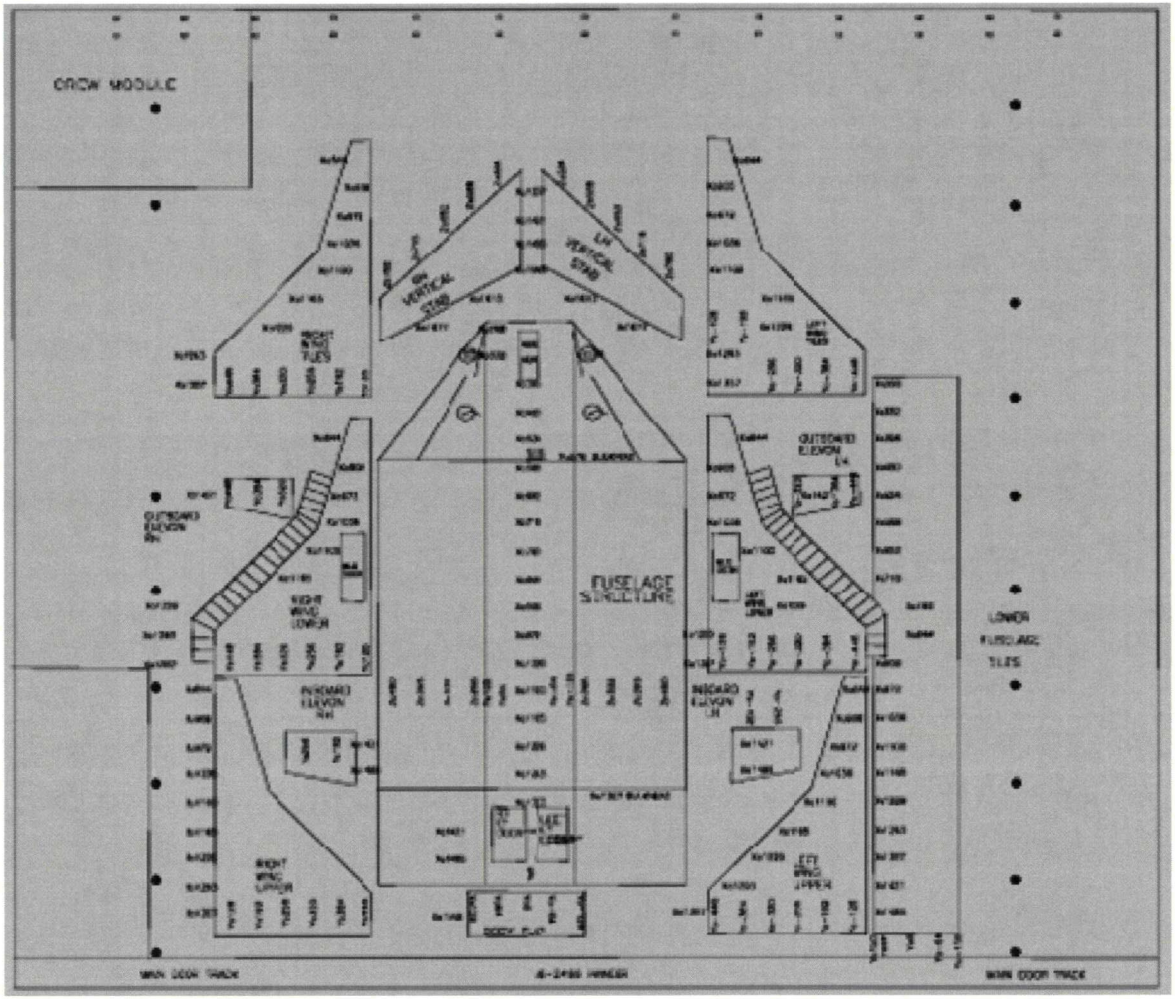
Reconstruction Plan



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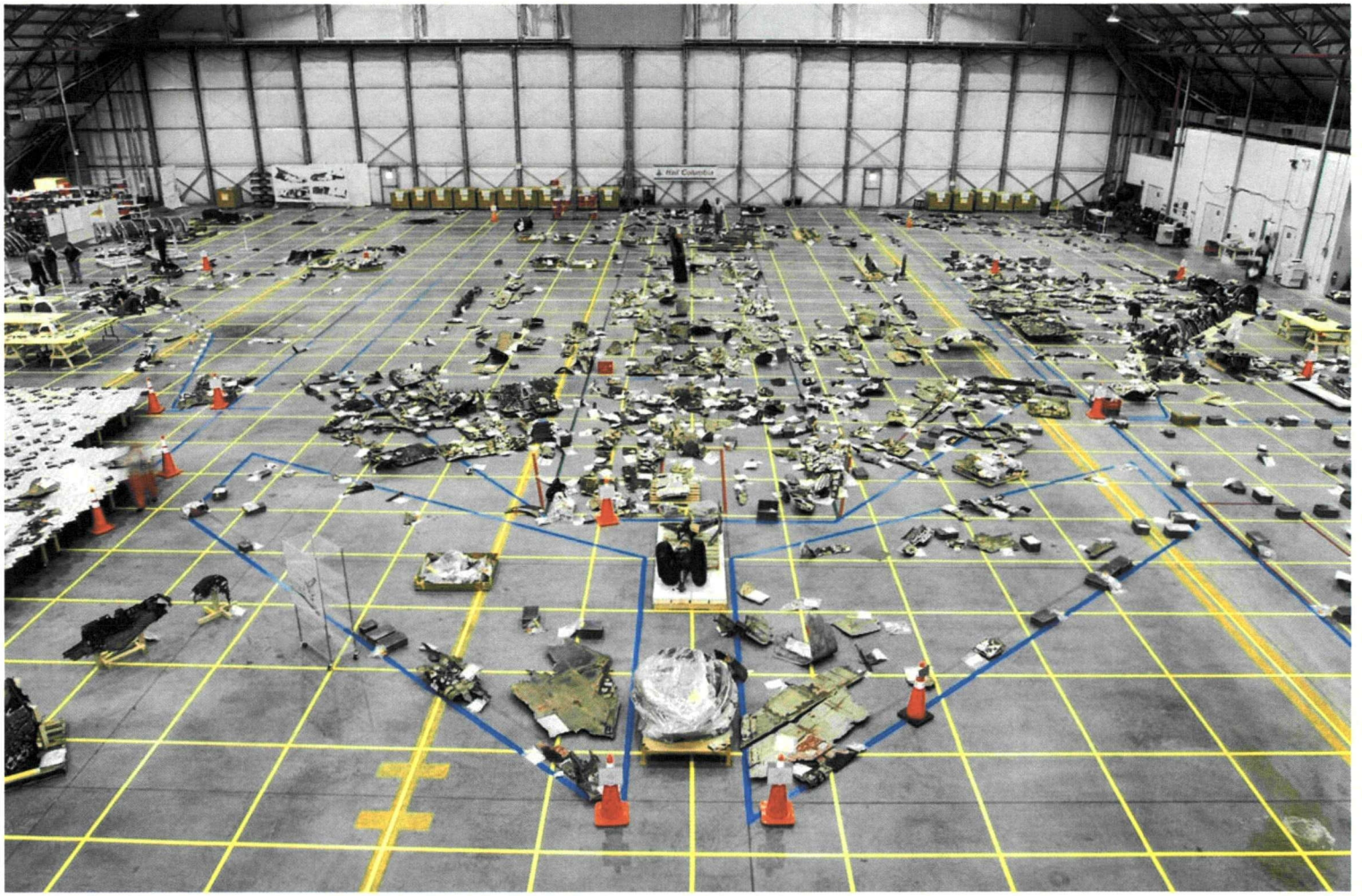
Reconstruction Hanger



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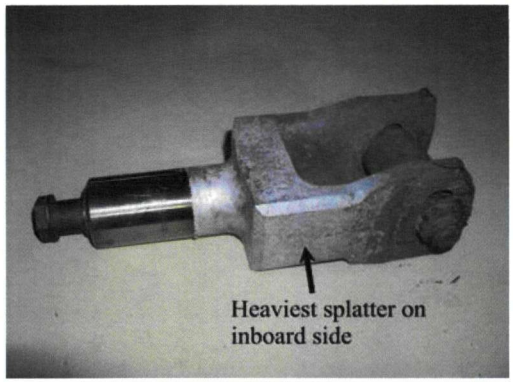
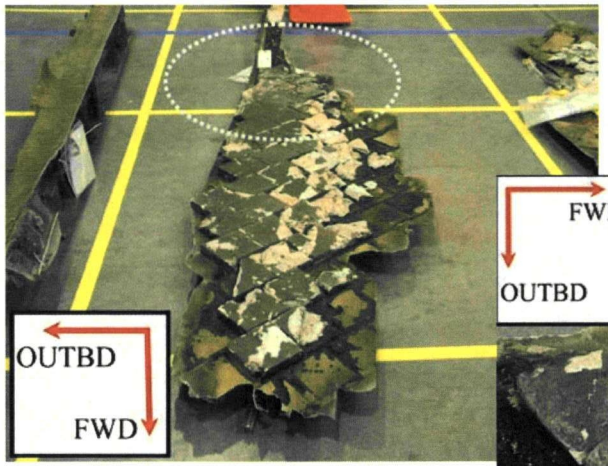
Early Analysis – Left MLG Door Area

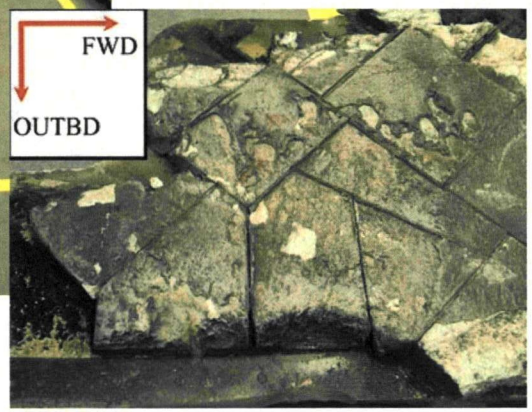
LH MLG Strut

MLG Tires



MLG Door Up-lock





Skin Panel

Emphasis Switched to Left Hand Wing Leading Edge

- Evidence of extreme overheating and heavy deposits on specific WLE hardware appeared to correlate with the instrumentation and senor data (MADS Recorder)
- To validate proposed break-up scenarios under consideration the investigation was concentrated on three areas of interest associated with the Wing leading Edge Subsystem (LESS):
  - Carrier Panel Tiles
  - RCC Panels
  - Wing substructure attach hardware

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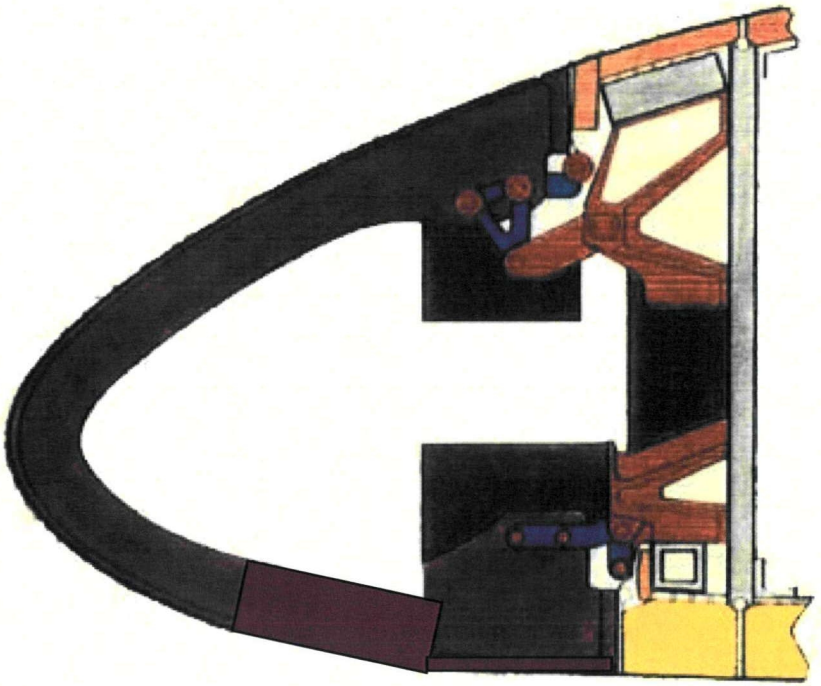
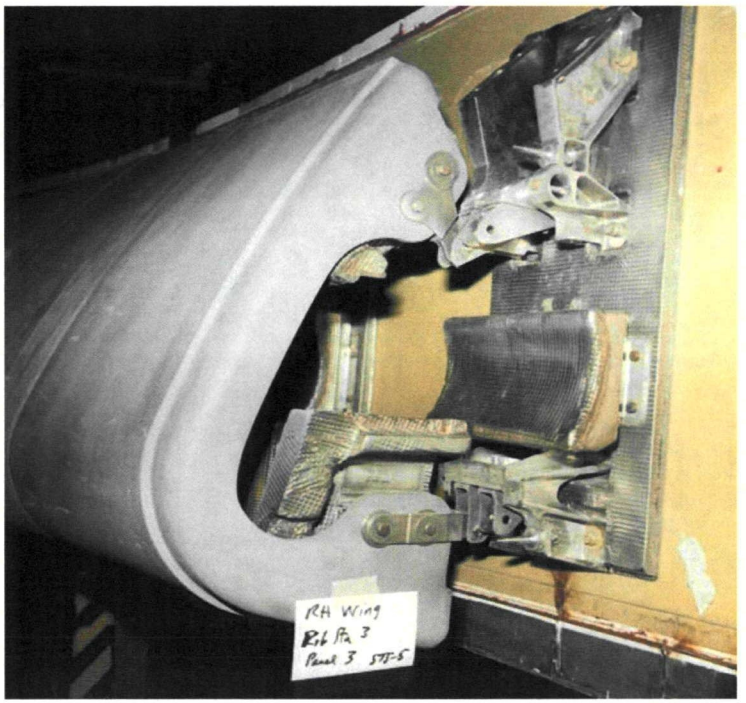
Wing Leading Edge Subsystem (LESS)





3D Reconstruction of Left WLE

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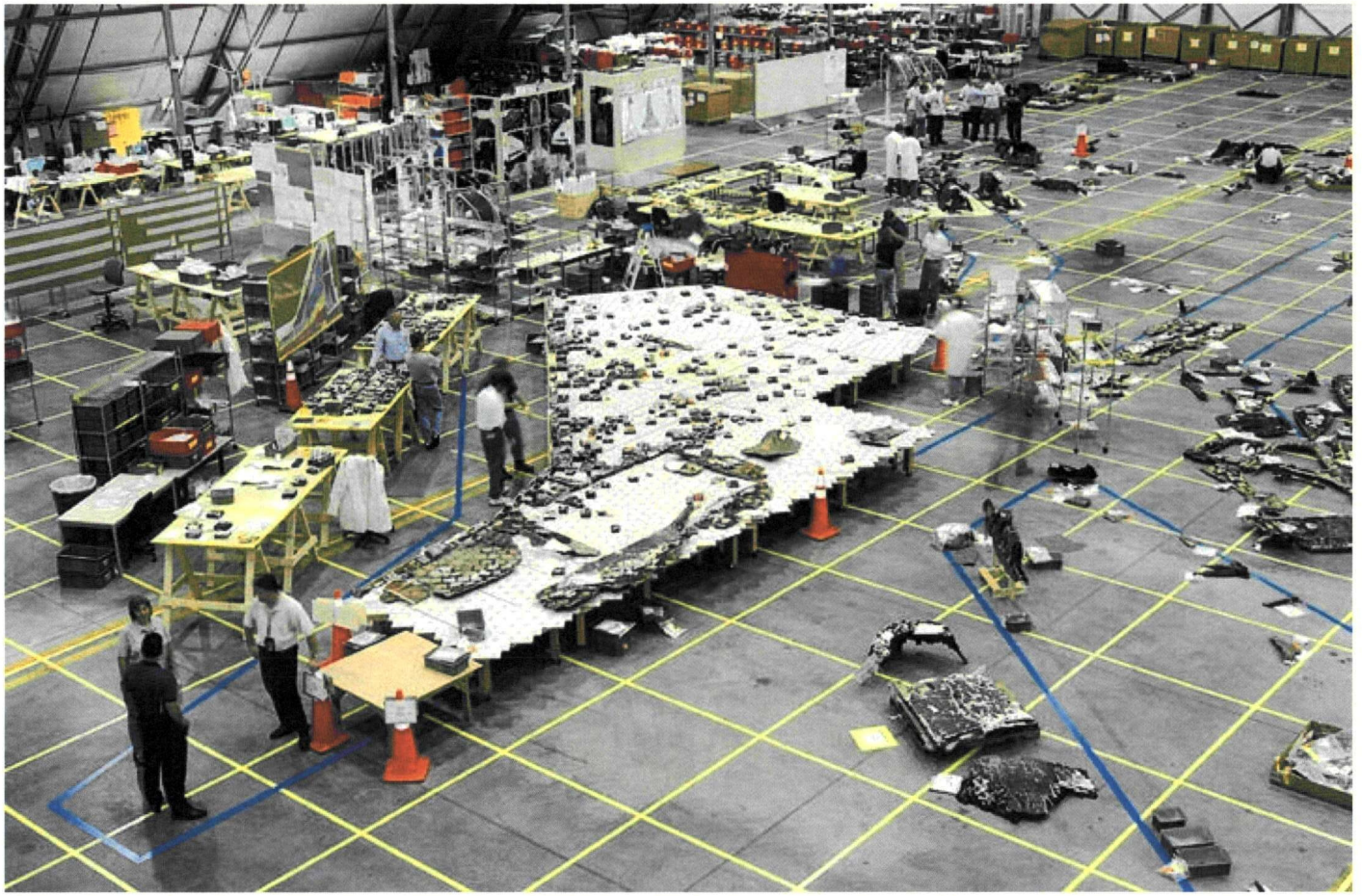
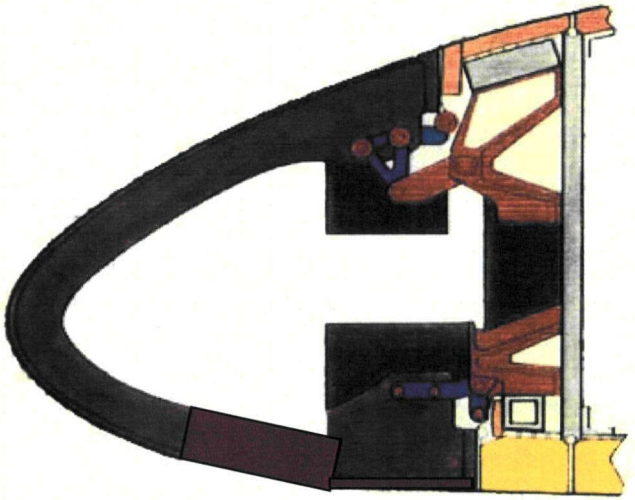
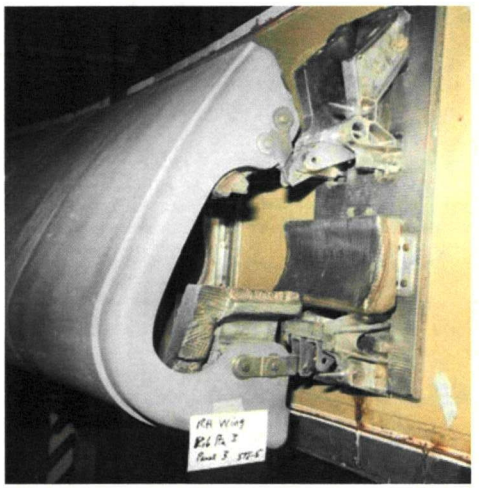
Left Wing Tile Table



LESS Observations

- Unique indications of heat damage:
  - Excessive overheating and slumping of carrier panel tiles
  - Eroded and knife-edged RCC rib sections
  - Heavy deposits on select pieces of RCC panels





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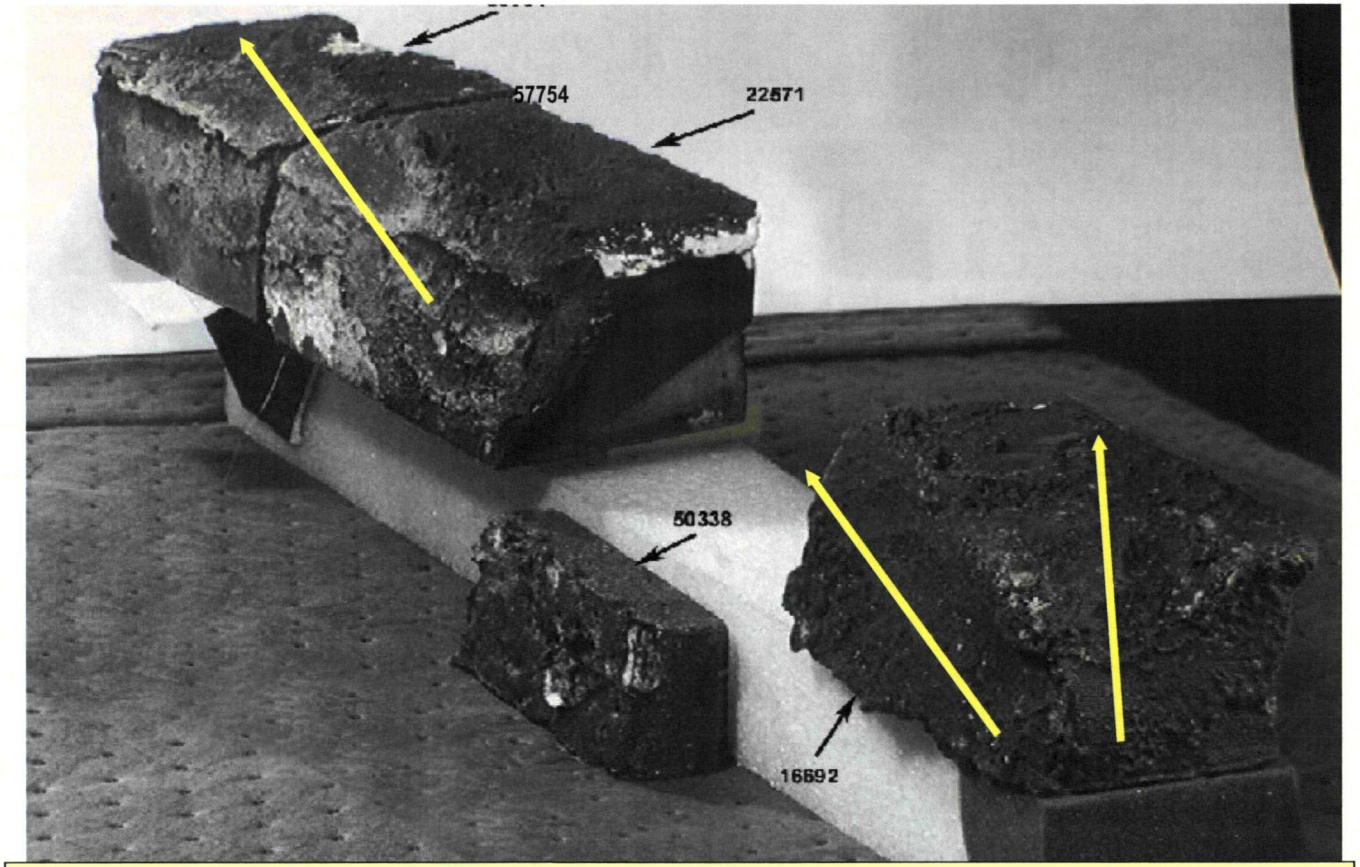
Reconstructed View of Lower C/P 9 Tile



Slumping and erosion patterns suggest plasma flow across the carrier panel tile (from 8 toward 10)

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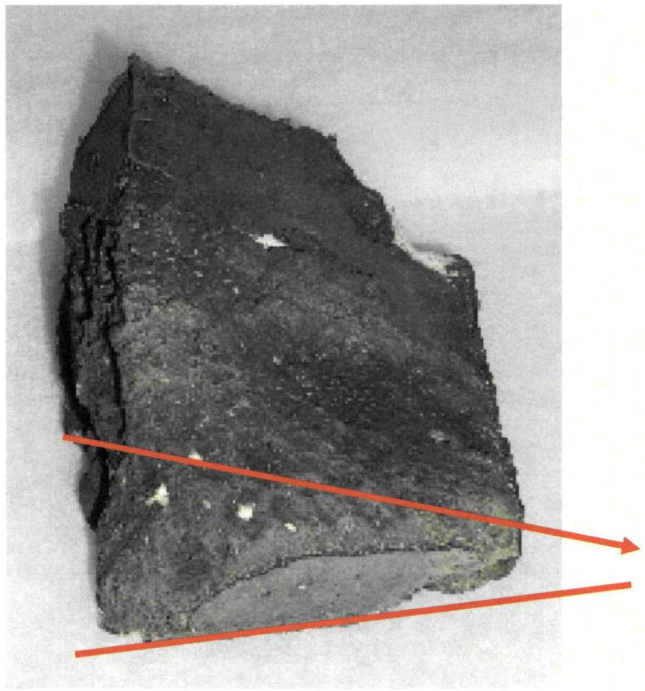
Carrier Panel 8 - Upper



Item 50336 (V070-199715-074)

Slumping and erosion patterns suggest plasma flow out of leading edge cavity (consistent with vent)

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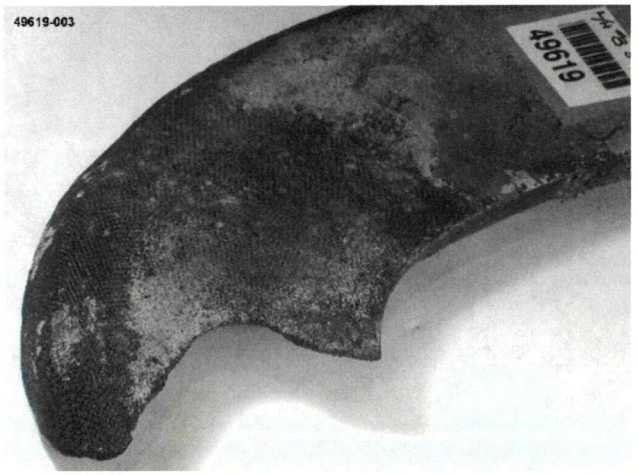
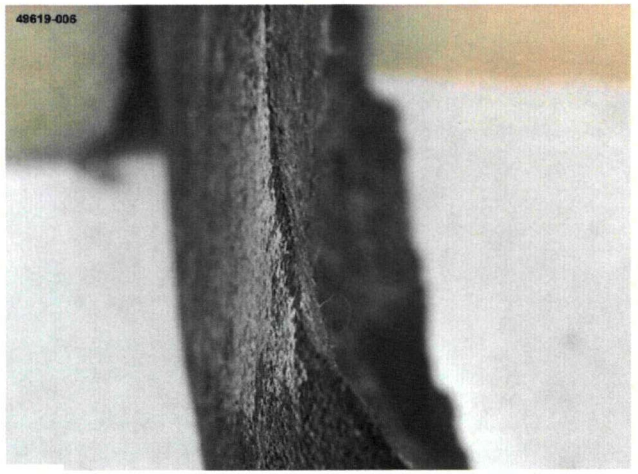
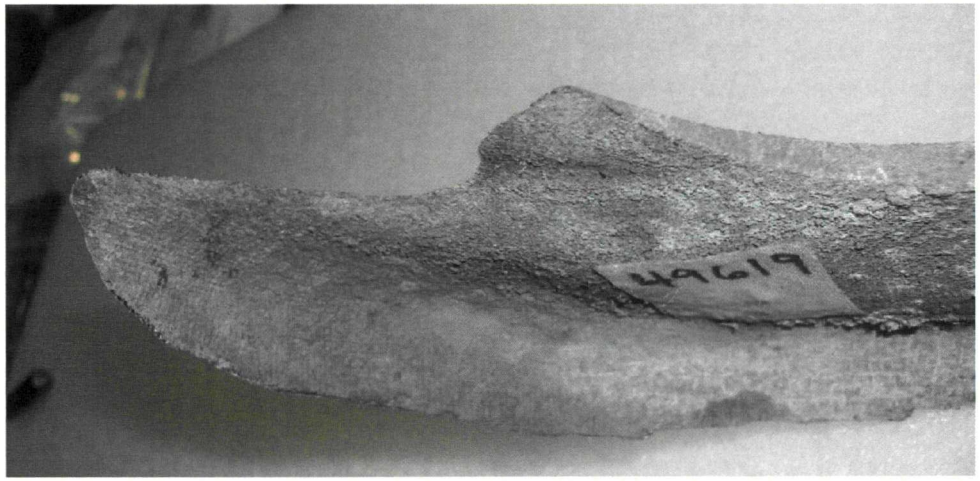
Erosion on Panel 8 Upper Outboard Rib

Outboard apex





Item 49619



Close-ups of knife edge, note fibers not visible on internal surface of panel due to deposits.

Rib tapers from design thickness of .365" to .05".

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Erosion on Gap Surfaces of Panel 8 Outboard Lug & Matching Heel Piece

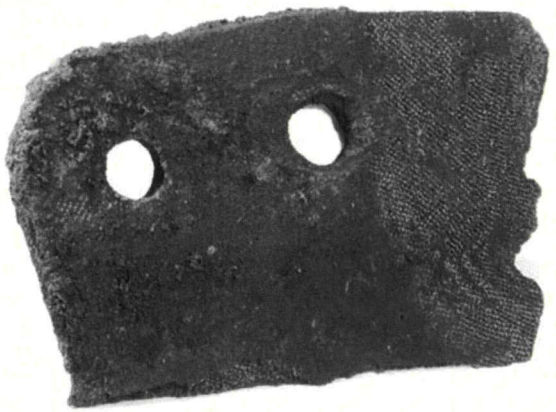
24724-047

58291

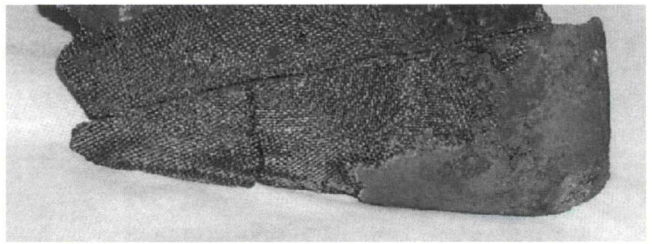
External/Outboard surfaces:

- Matching eroded plies between items 24724 and 58291, shows heat flow external to the panel while panel heel and lug were attached
- Metallic deposits at lug attach points - evidence that metallic deposited after lug no longer attached to fitting
- Inconel bushings missing at holes

24724-041

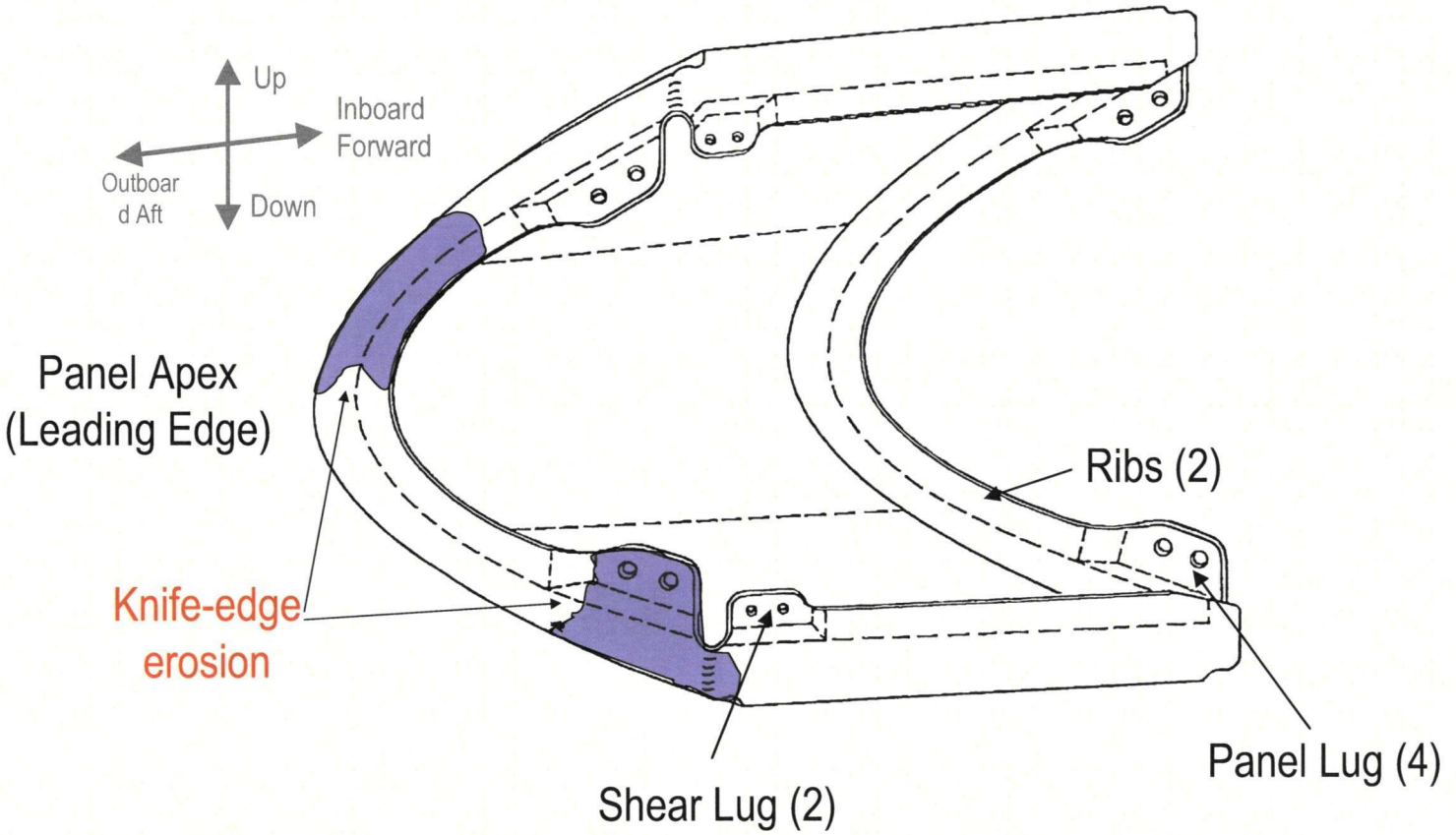


Lug fragment tapers from design thickness of .499", to a Knife Edge with a minimum thickness of 0.063"



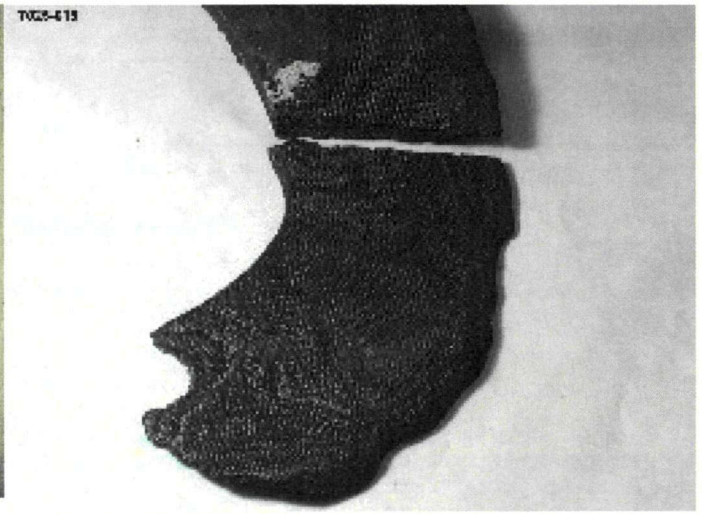
Heel fragment tapers from design thickness of .233", to a Knife Edge with a minimum thickness of 0.052"

RCC Panel 8 Erosion Features

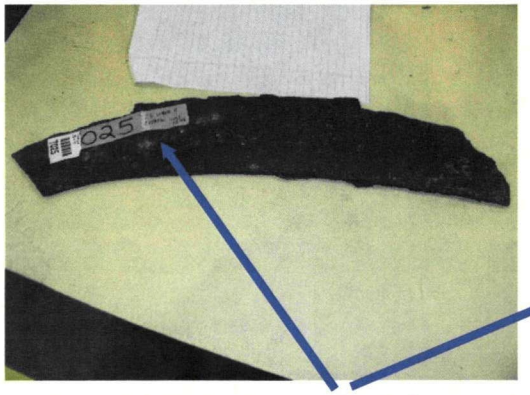


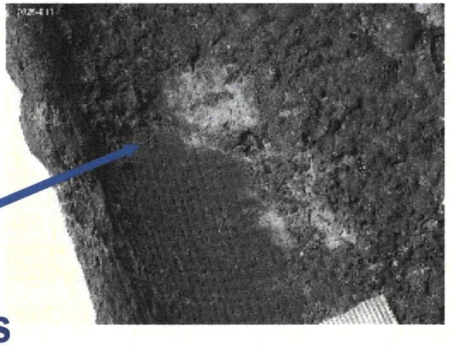
Erosion indicates prolonged exposure to plasma heating

Erosion on Panel 9 Upper Inboard Rib



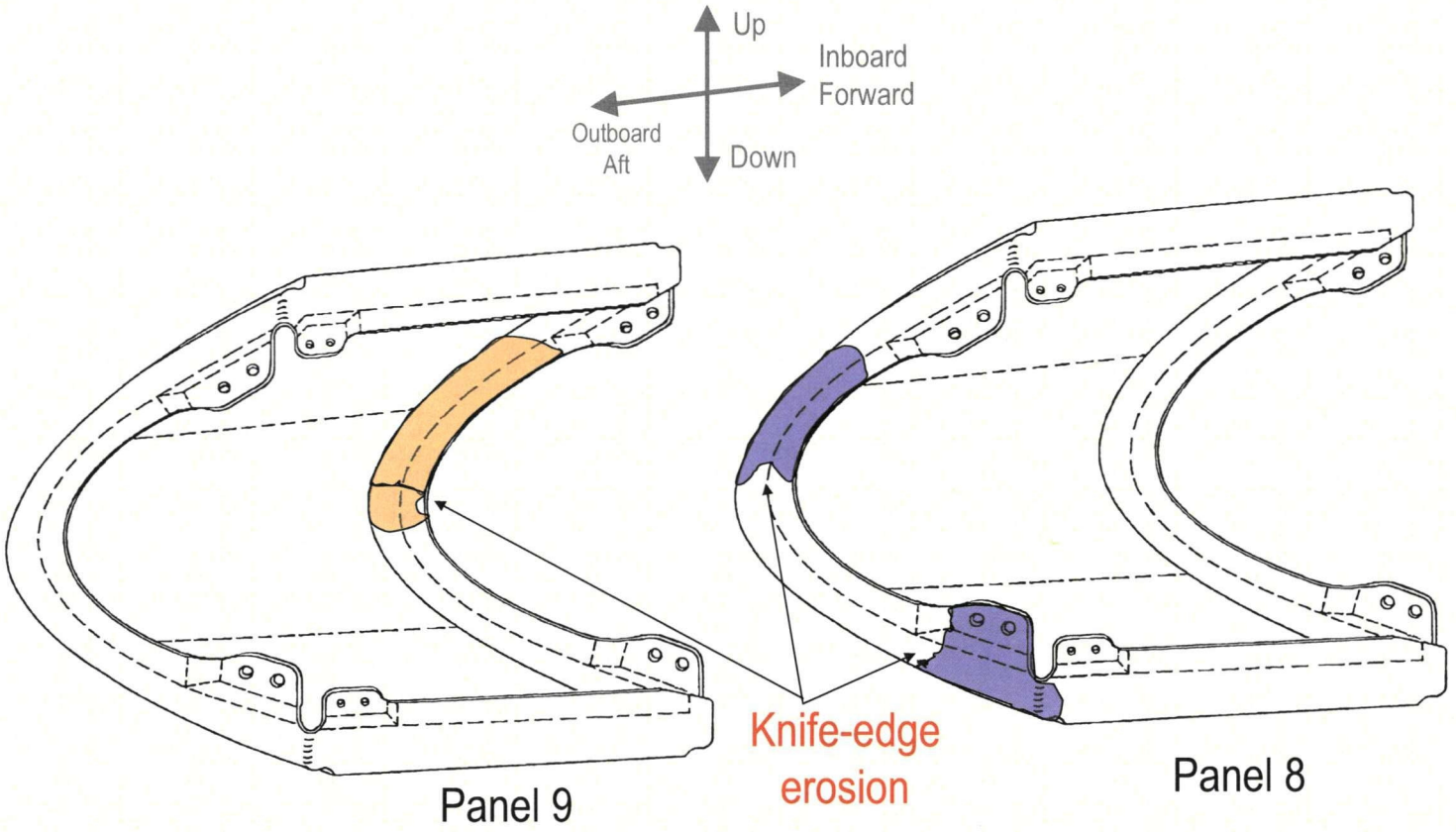
7025 to 52018 interface shows severe thermal erosion – thickness ranges from 0.270 to knife edge of 0.040





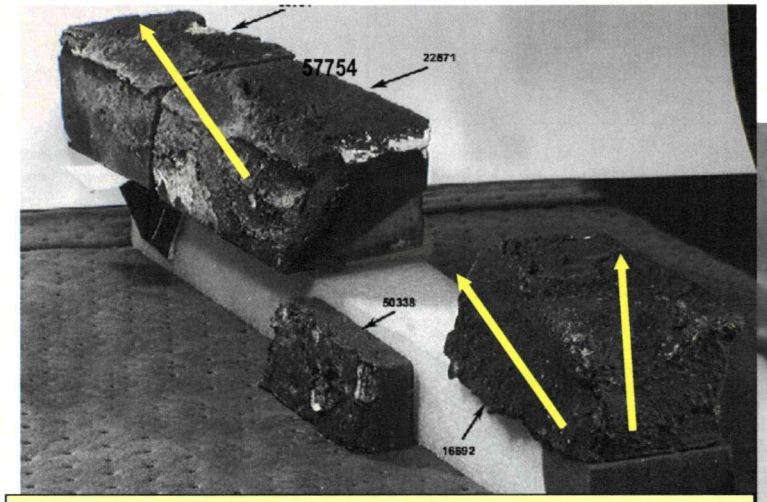
7025 internal side shows presence of metallic deposits

RCC Panels 8 & 9 Erosion Features



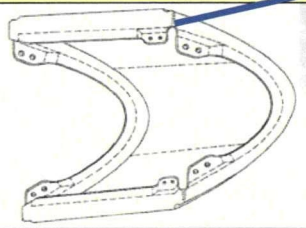
Erosion indicates prolonged exposure in the panel 8-9 joint area.

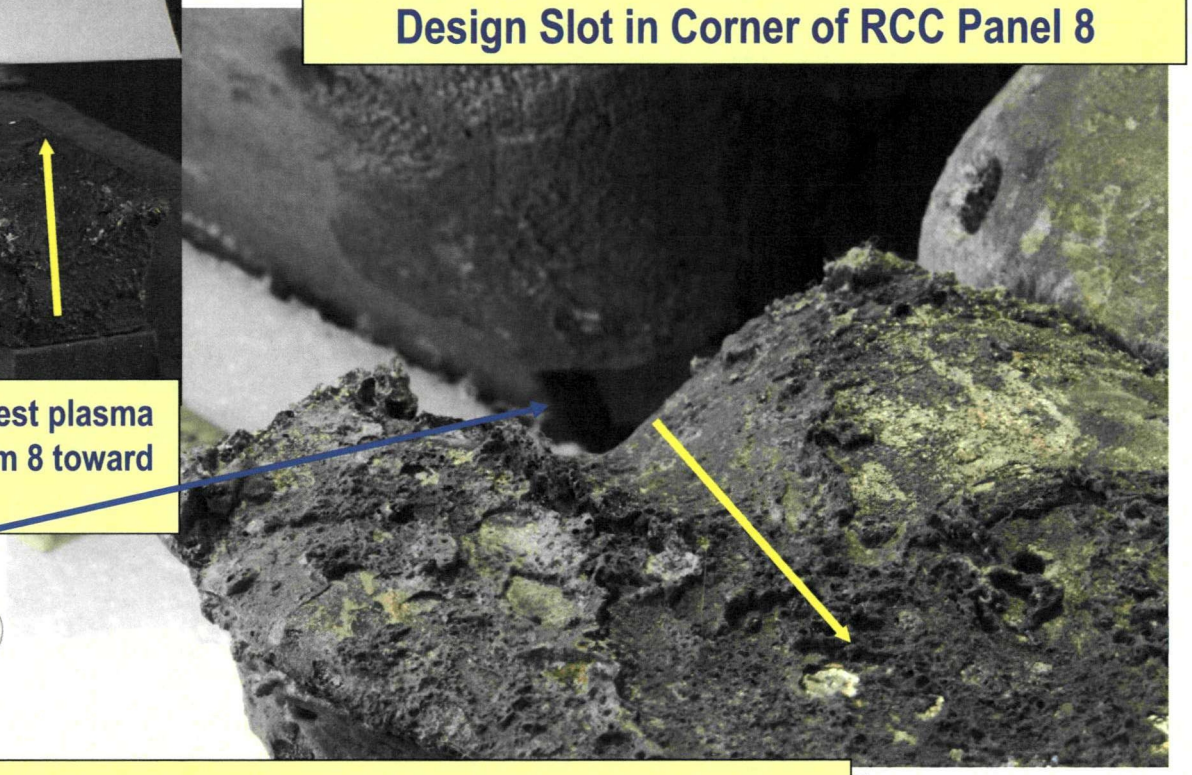
Slumping Source for Carrier Panel 9 Tile was Revealed



Slumping and erosion patterns suggest plasma flow across the carrier panel tile (from 8 toward 10)

Slumping of C/P 9 Tile #1 Corresponds with Design Slot in Corner of RCC Panel 8





Evidence of Hot Gas Flow Exiting Design Slot Indicates Significant Breach Was Into Panel 8

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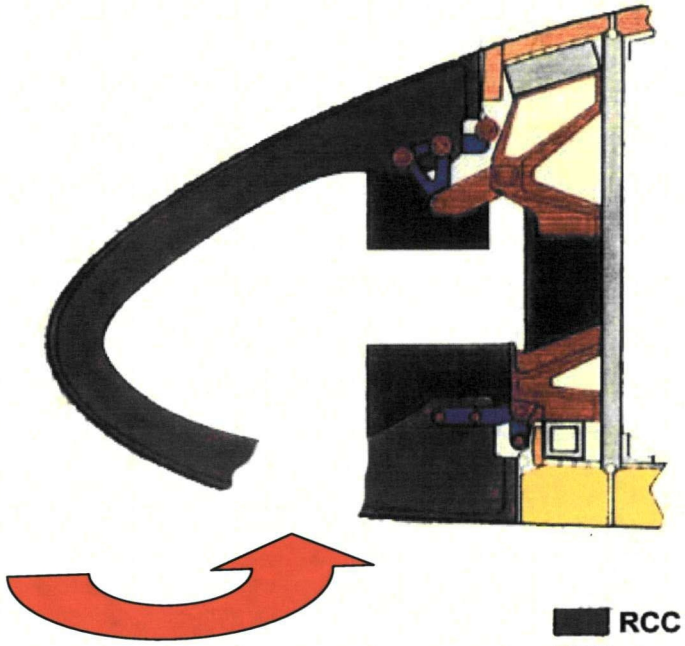
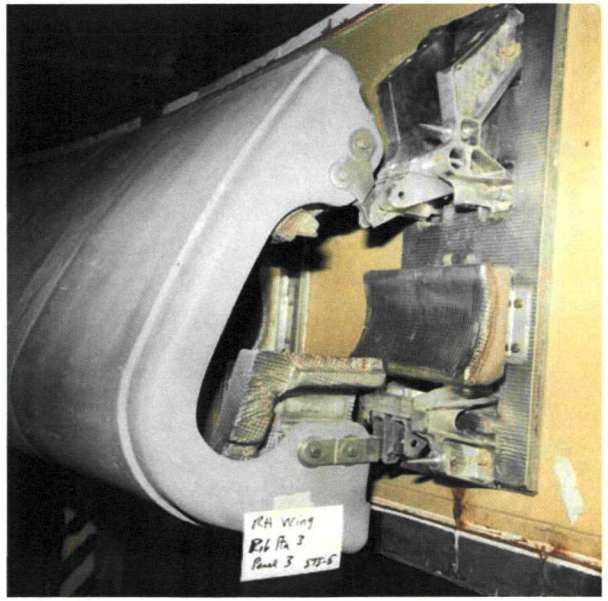
Debris Indicates Highest Probability Initiation Site

- Wing failure initiated in the panel 8 area
  - Most likely at the panel 8 area near 8-9 joint
  - Condition existed before or shortly after entry interface





RCC
Aluminum
LI2200
LI900
Inconel-Dynaflex
Inconel 718
A-286 steel

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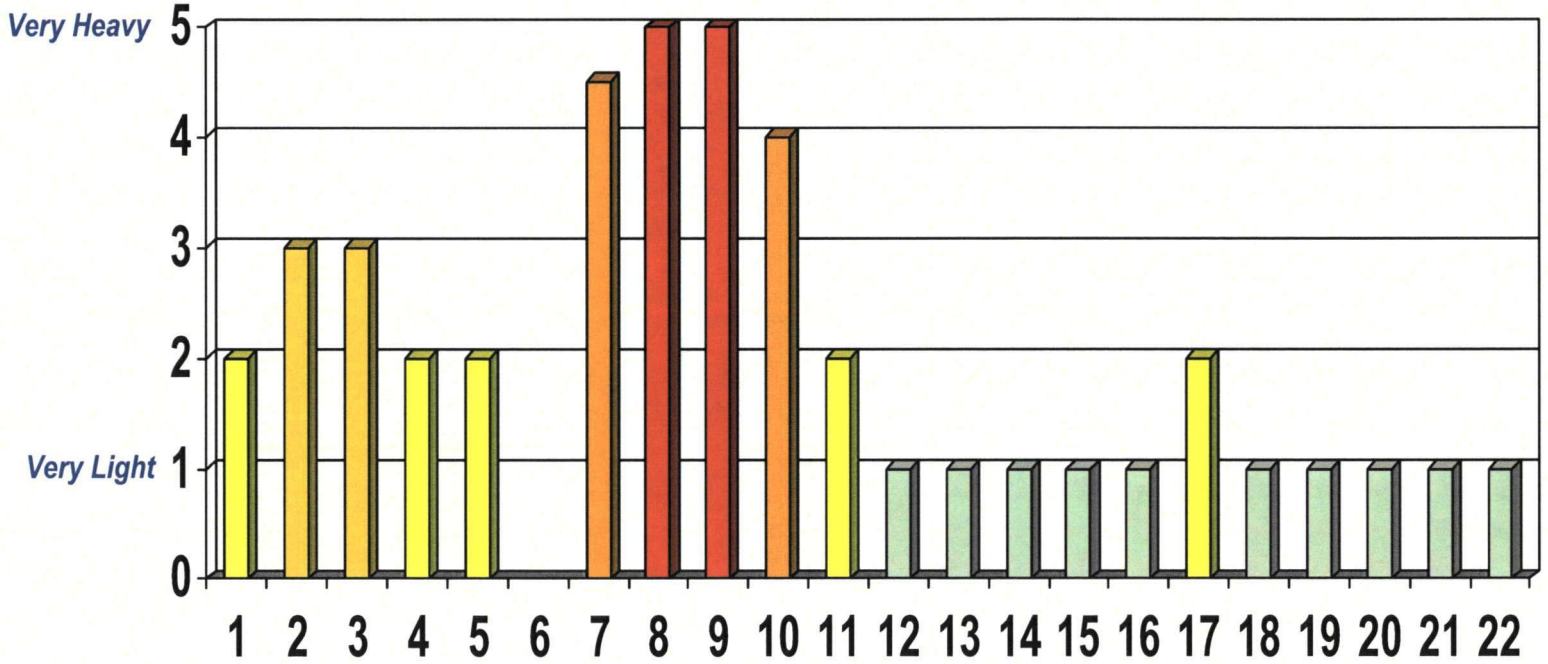
Relative Metallic Deposition on L/H Wing Materials

Qualitative deposition assessment:
from "Very Light" to "Very Heavy"



Distribution of metallic deposition <u>volume</u>
was centered around panels 8 & 9

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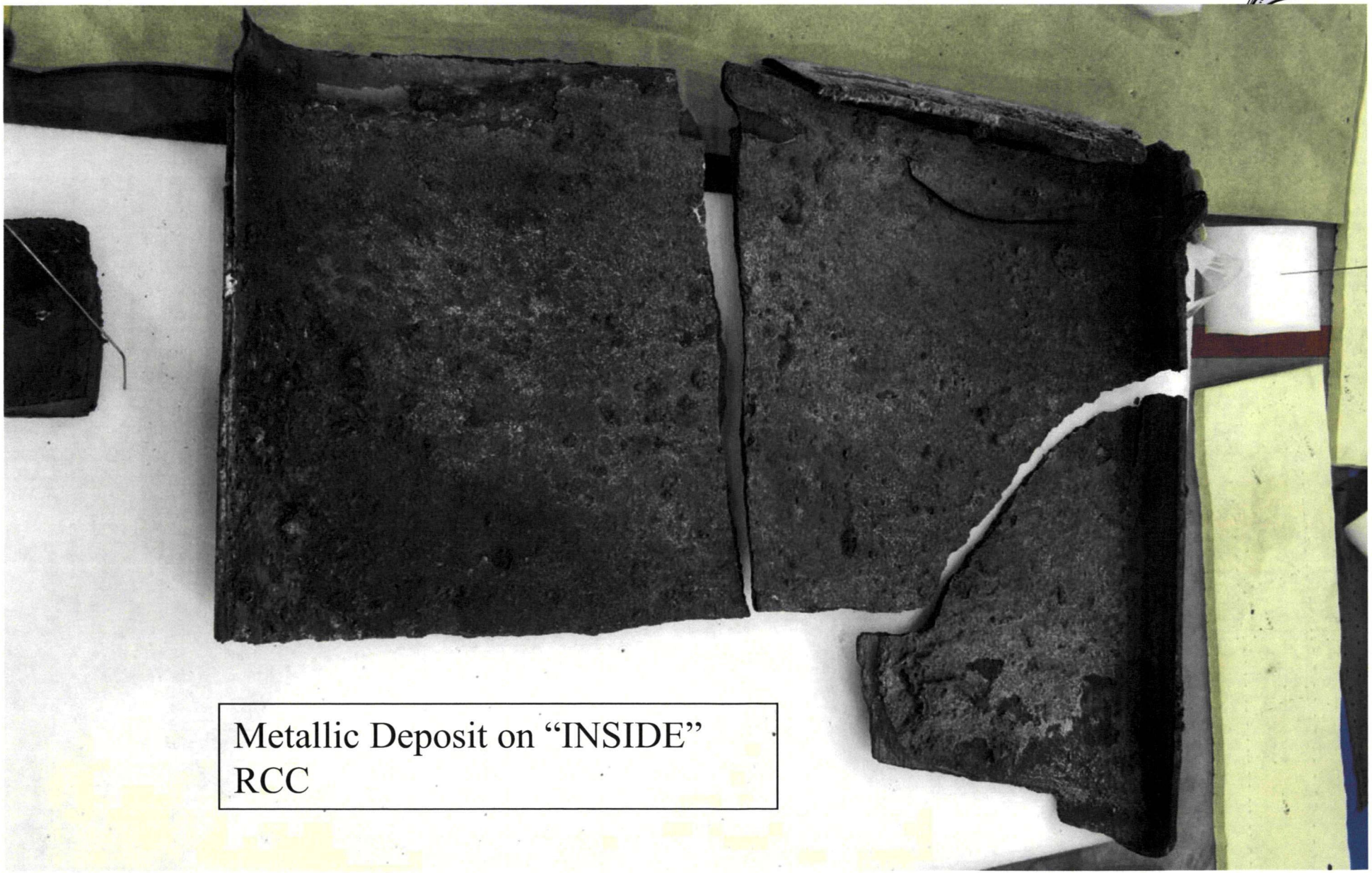
Metallic Deposit Example, LH RCC 8



Metallic Deposit on "INSIDE" RCC

High Level Questions

Sample the metallic deposits on RCC & Tiles to:

- Identify the location of breach in the wing leading edge.
- Identify the sequence of deposition/events
- Understand plasma flow direction and related thermal damage.

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Analysis Plan Challenges

- Understand Pros and Cons of Analysis Techniques (destructive and non-destructive)
  - Objective is to downselect analysis techniques fast.
- What are the leading edge materials?
- Understand Chemistry of reactions with atmospheric elements.
- Understand effects of melting and mixing of different materials.
- All analysis to be complete by end of May, 2003. Wrap-up in June.

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Analysis Approach

- Radiograph RCC panels & Tiles
- Strategically locate samples - minimize the sample count. Two samples of each feature.
- Use diagnostic techniques (X-section, SEM, Microprobe, XRD) to identify:
  - Content of metallic deposits
  - Layering of metallic deposits
- Use "Interpretation Criteria" to correlate deposit analysis <==> WLE source material

Apply results to ALL radiographs and visual features to answer the high level questions.

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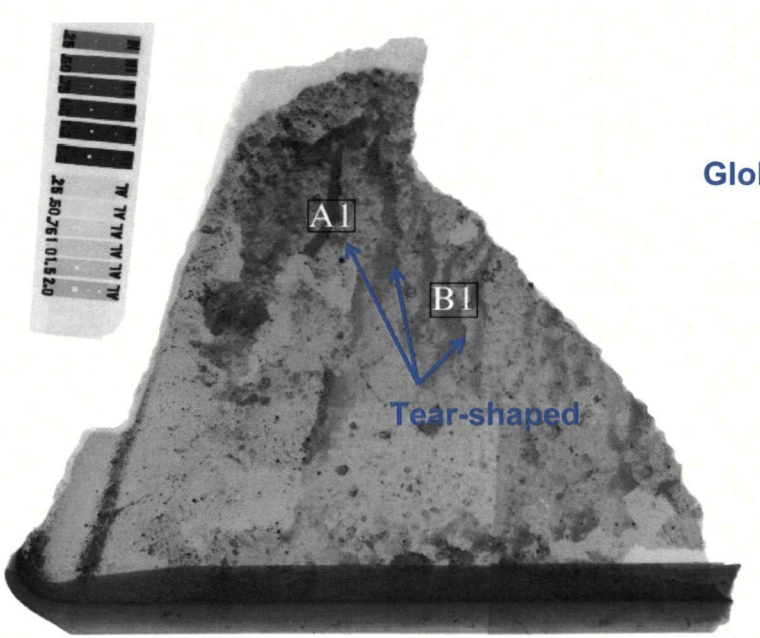
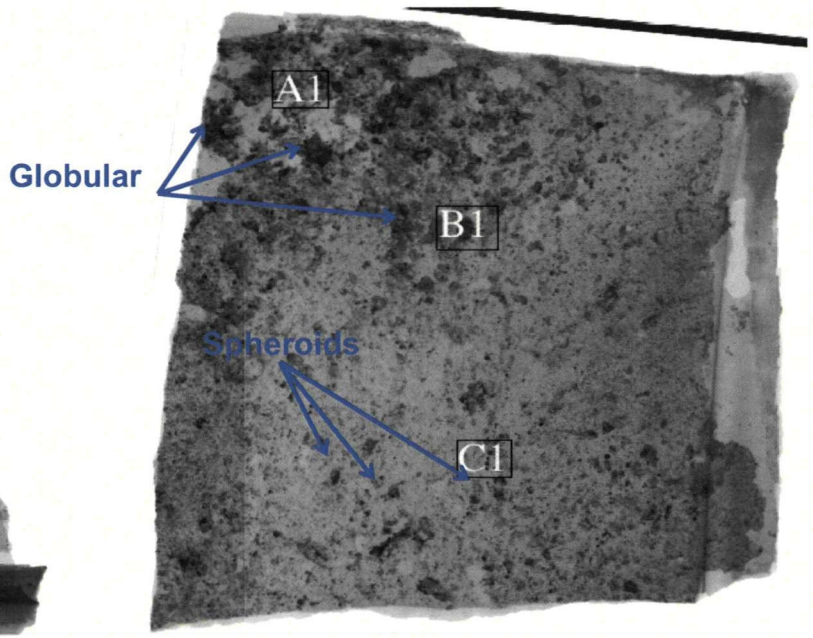
Radiographic Features

- Four types of deposit patterns were identified from LH RCC Panel 8:
  - Uniformly thick; Spheroidal; Tear-shaped; Globular





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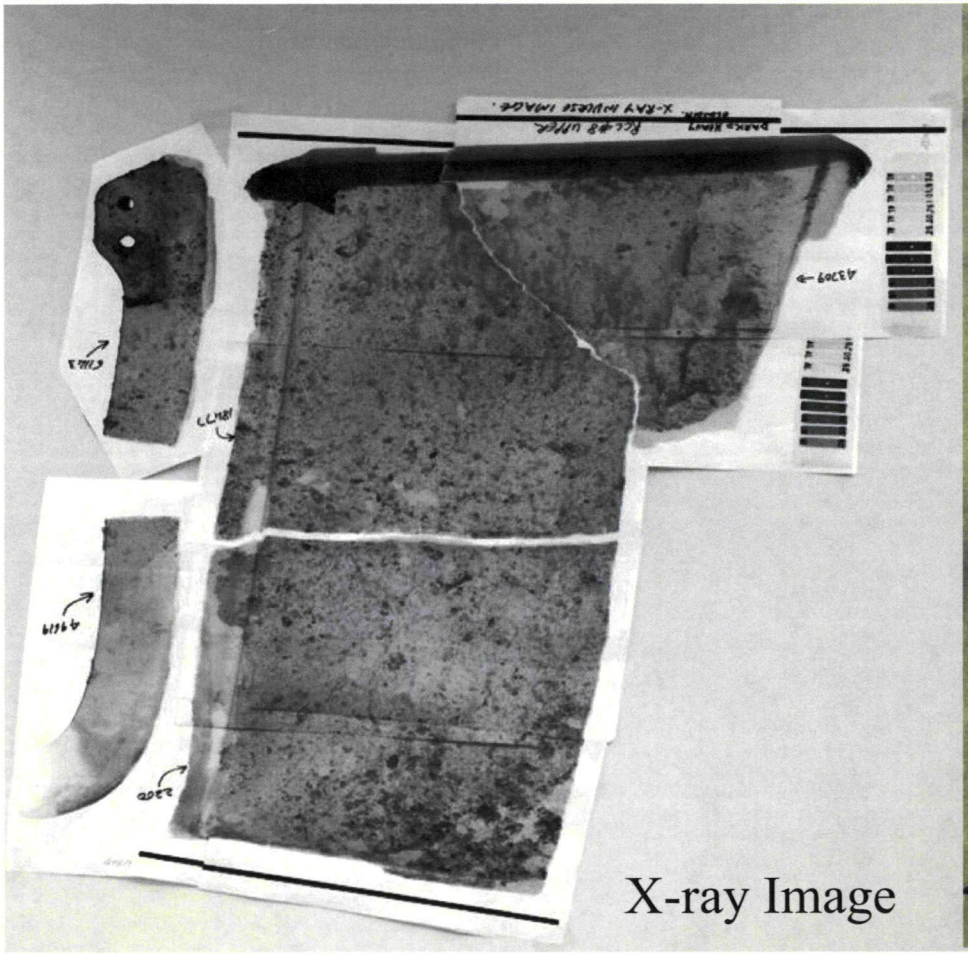
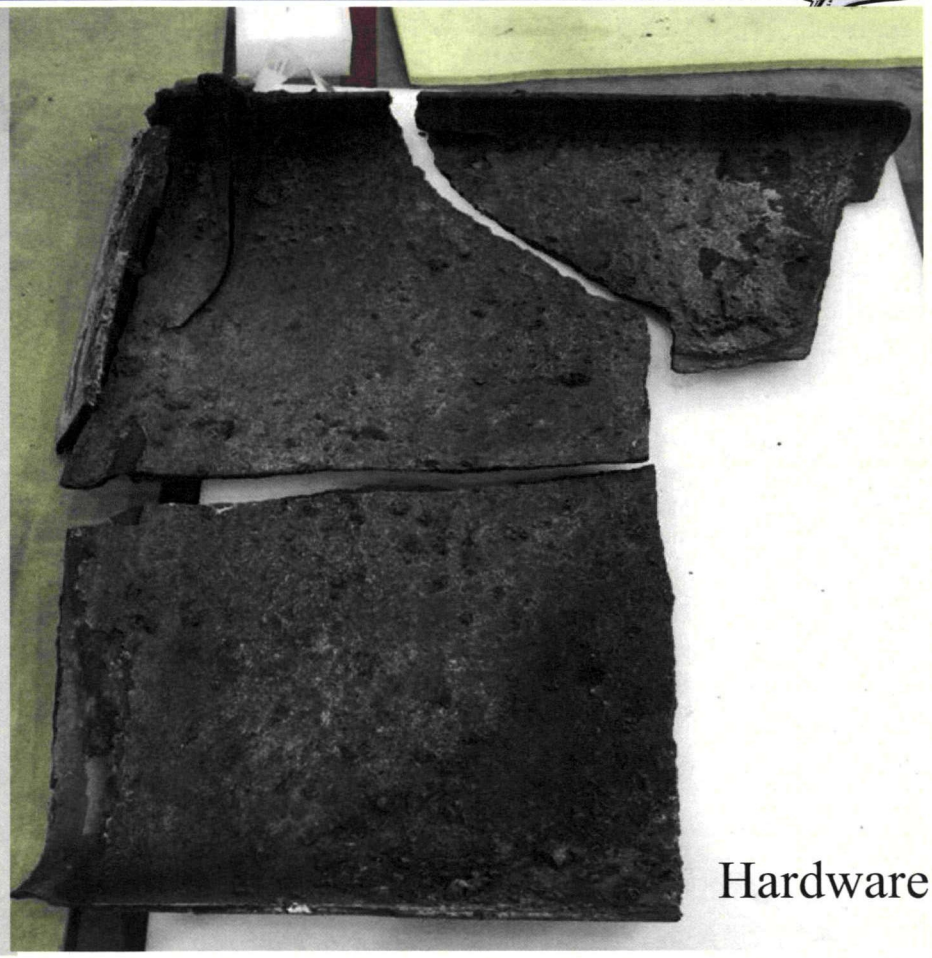
Radiography WLE LH Panel 8

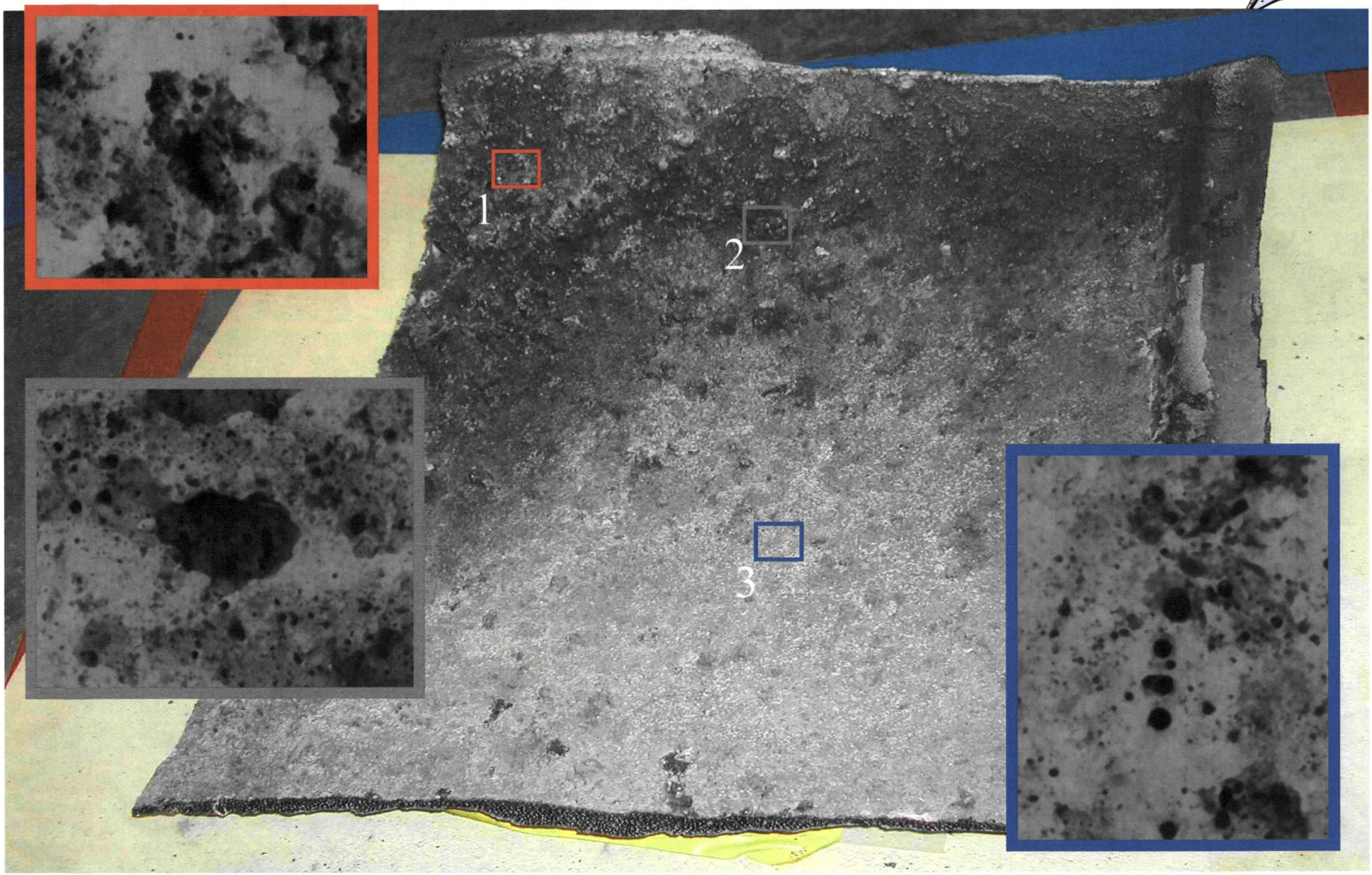


X-ray Image

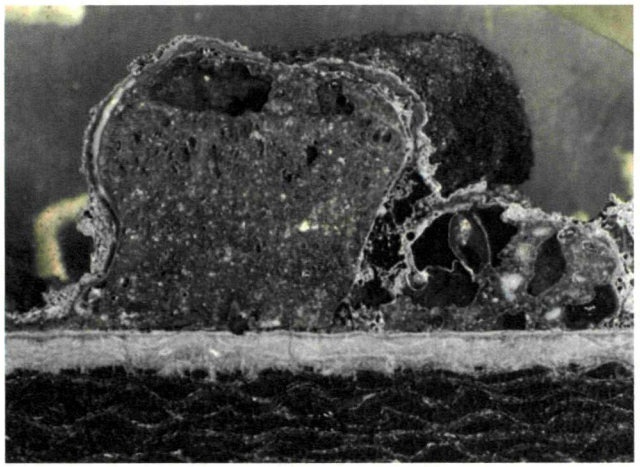


Hardware

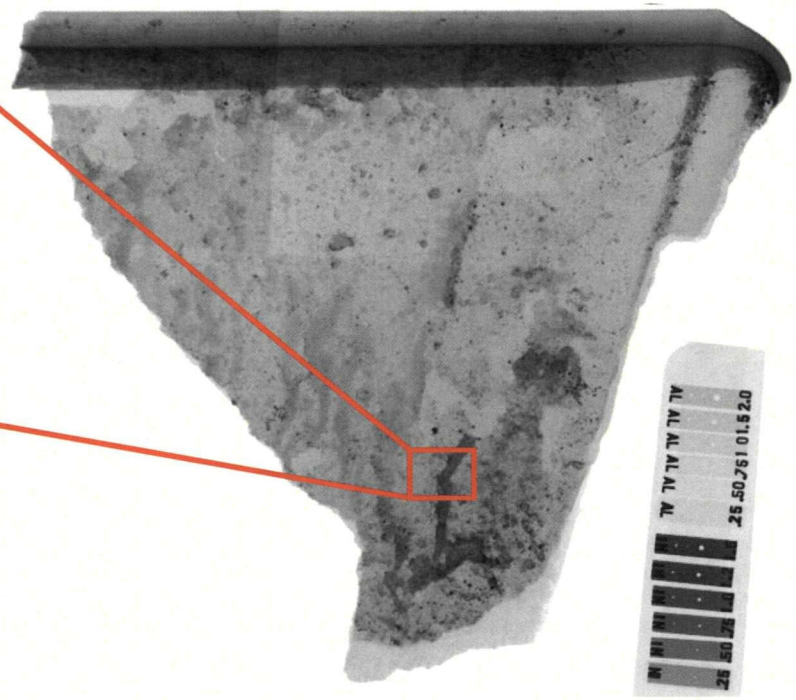
LH RCC 8 Upper Apex



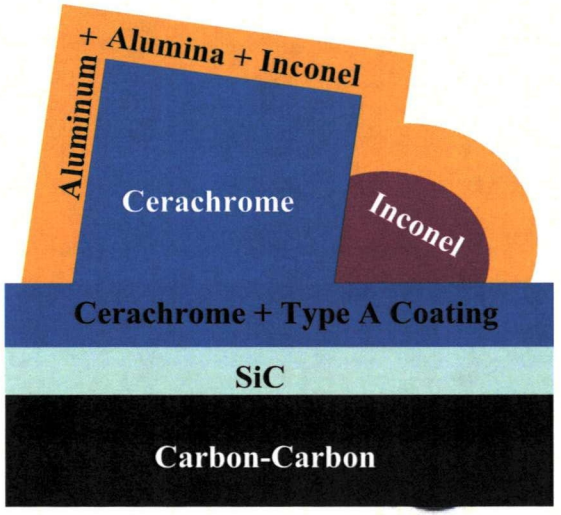
LH RCC 8 – Deposit Feature: Thick Tear Shaped



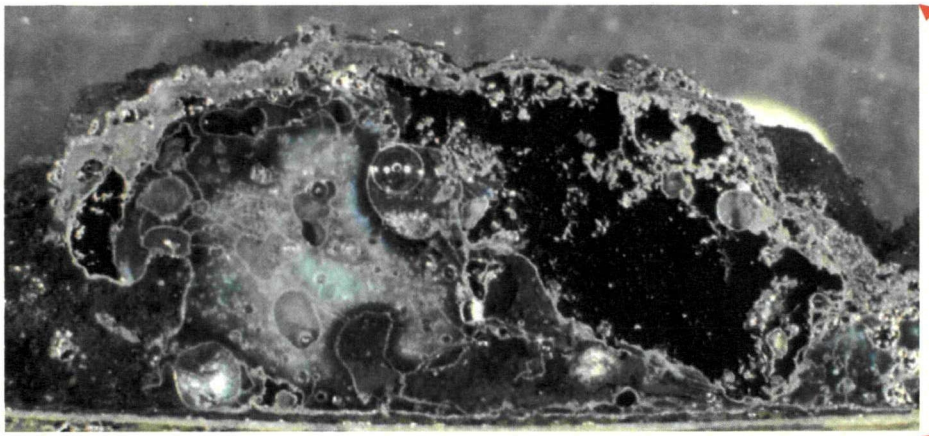
Item 43709, Sample 2A1



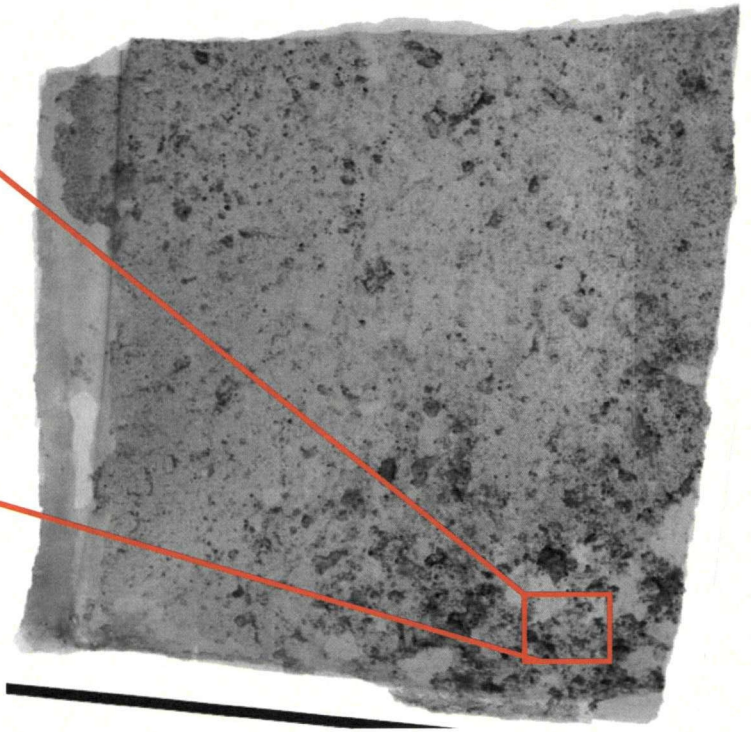
Radiograph of Item 43709



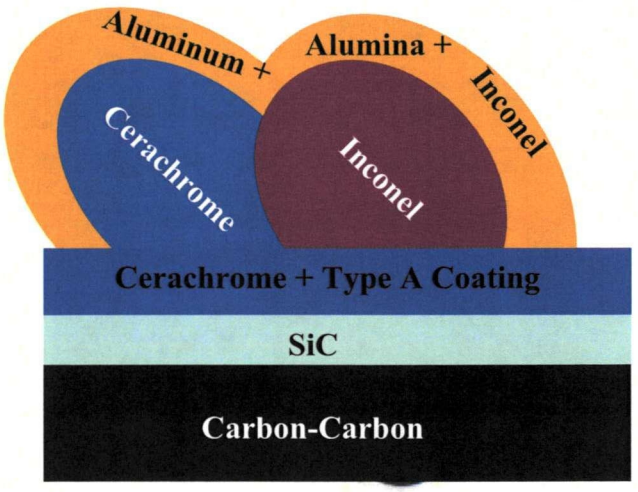
LH RCC 8 – Deposit Feature: Thick Globules



Item 2200, Sample 6A1



Radiograph of Item 2200



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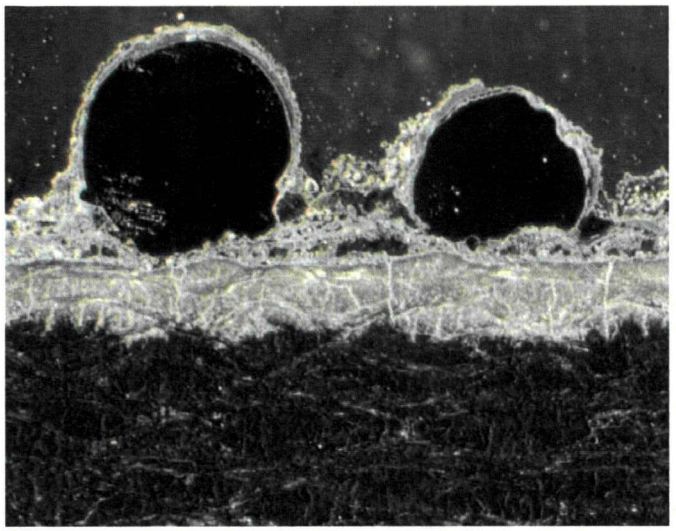
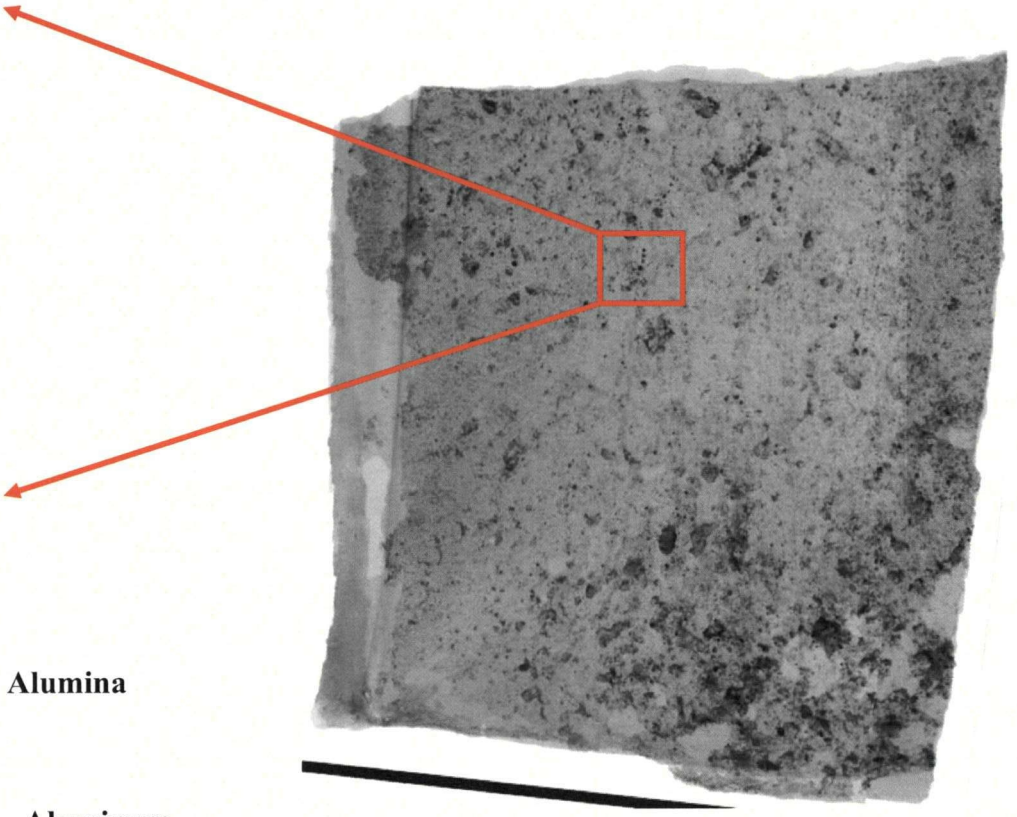
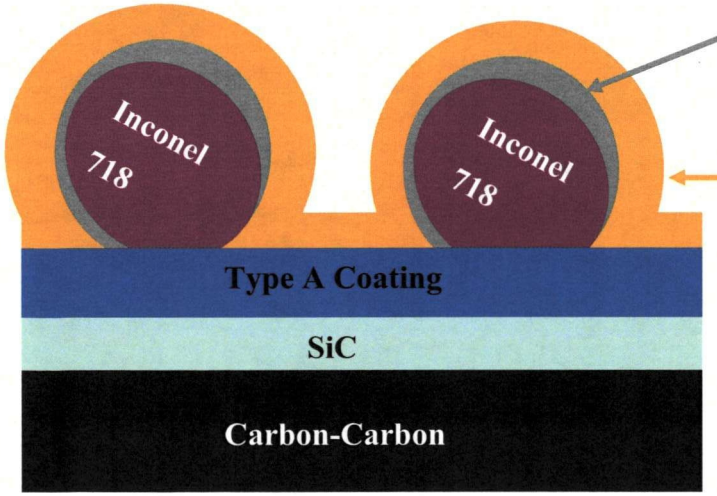
LH RCC 8 – Deposit Feature: Spheroids



Item 2200, Sample 6C1



Radiograph of Item 2200



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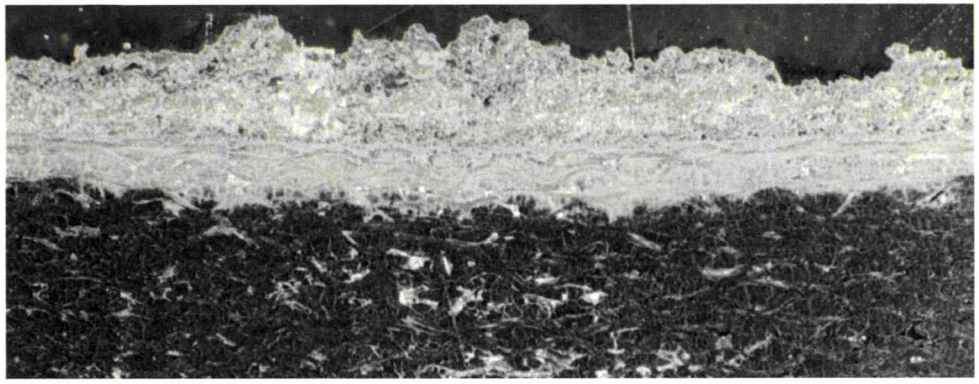
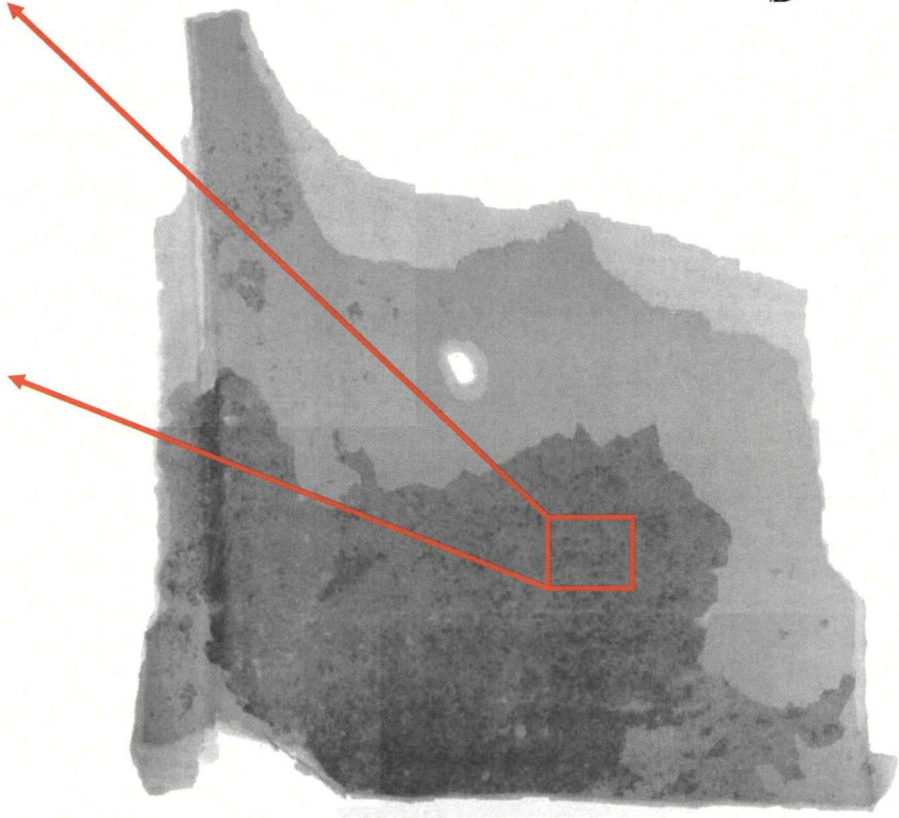
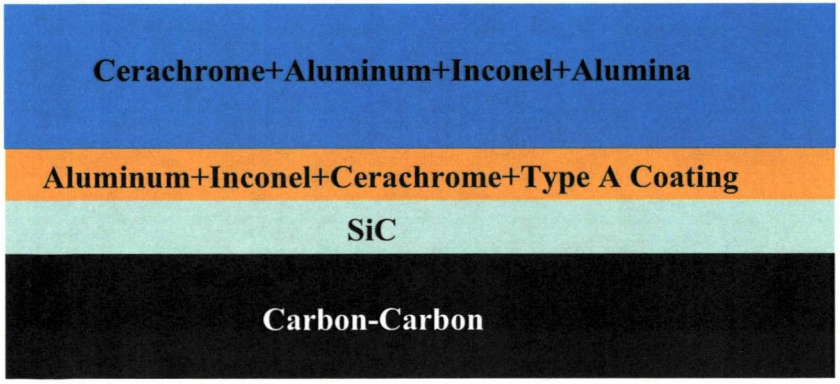
LH RCC 8 – Deposit Feature: Uniform Deposit



Item 16523, Sample 4A1



Radiograph of Item 16523



Significant Findings - Sampling LH RCC Panel 8

- Large amounts of melted ceramic cerachrome insulator
  - High temperature >3200°F
- No indication of stainless steel spar fittings (A286) in metallic deposits
  - Breach location away from spar fittings
- Cerachrome + Inconel in first deposited layers
  - Melting of spanner/foil/fittings + Insulator
- Aluminum deposition secondary event

Layering of metallic deposits suggests plasma impingement location

Distribution & shape of metallic deposits suggests plasma flow direction and deposition duration

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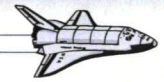
Significant Findings – Sampling All Other Panels



- Significant findings includes all LH RCC Panels except panel 8 and all RH RCC panels sampled
- All analyzed metallic deposit layers contain aluminum
  - CONCURRENT Spar/Inconel/Insulator melting
- Metallic deposits are is generally uniform and relatively thin
  - No region where melting was concentrated
    - i.e. plasma heating for short periods

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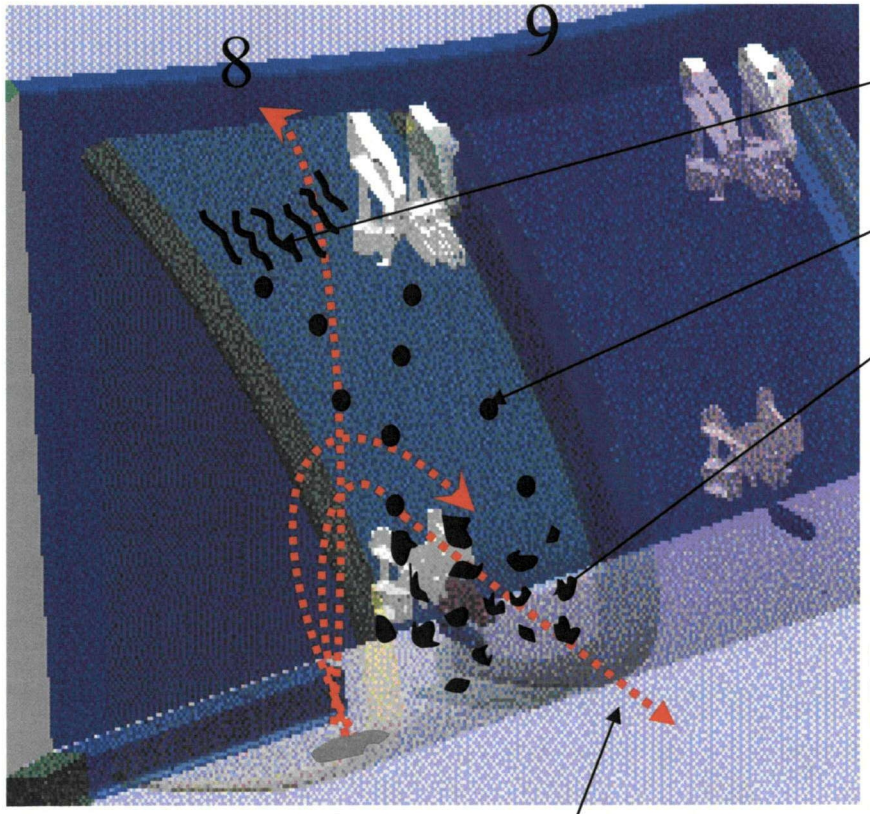
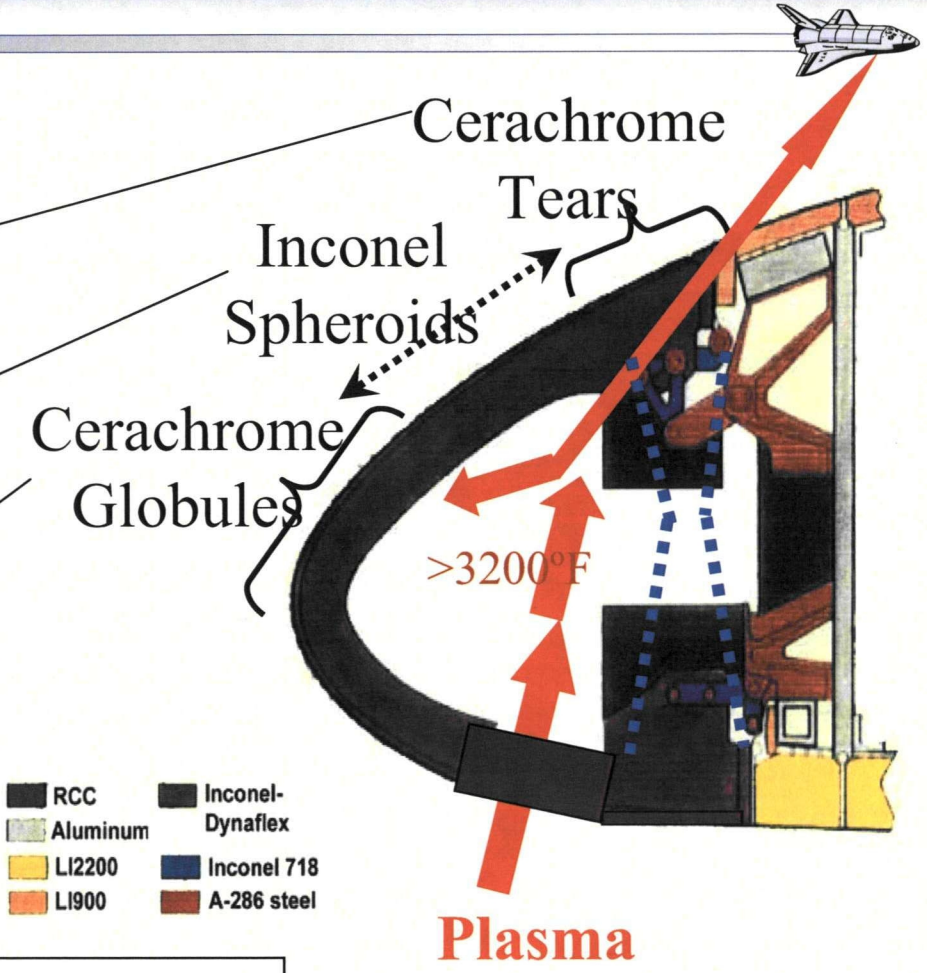
Proposed Breach Location and Plasma Flow





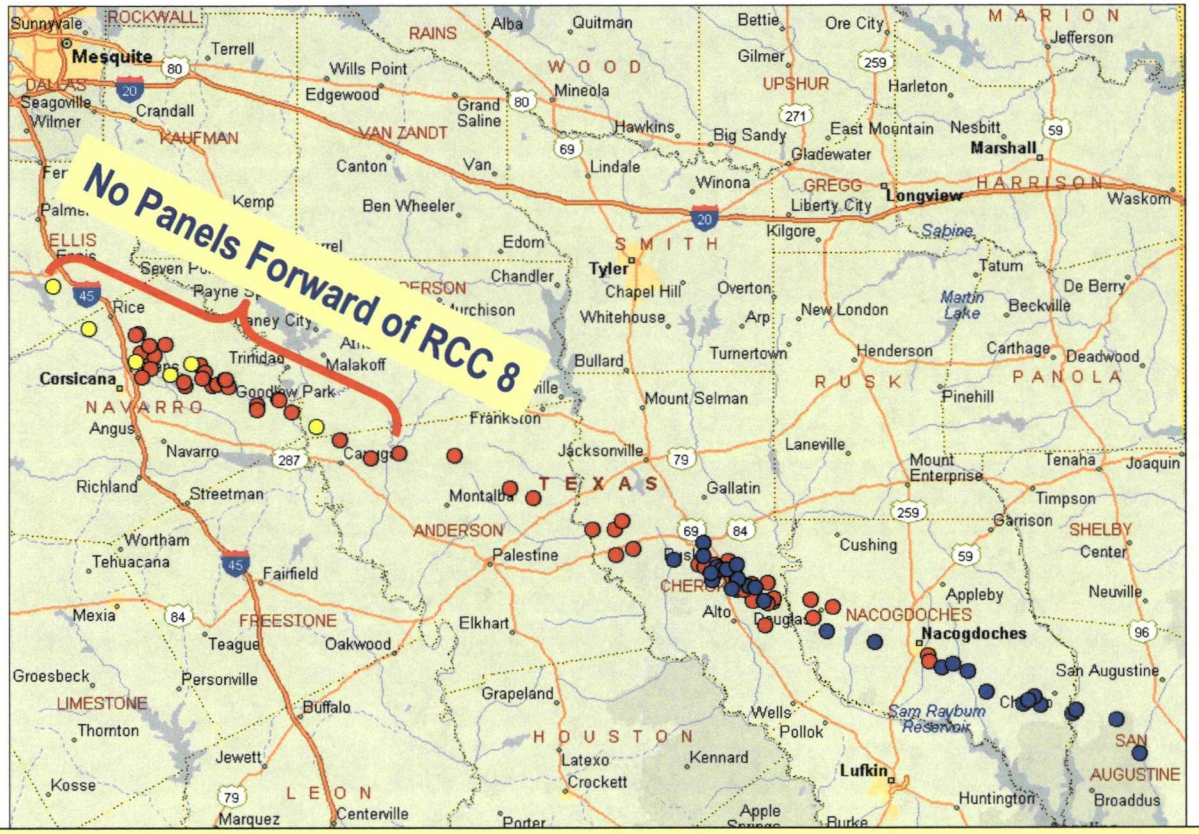
Flow Exiting through RCC 8 on to lower Carrier Panel 9 tiles

Corroborating Information - RCC Panel Debris Locations

Left Wing RCC

Left Wing Eroded RCC

Right Wing RCC



- Panels at RCC 8 and Aft Dropped First
- All Eroded RCC Pieces (in 8 & 9) Found to the West
- R/H Wing Panels and L/H Wing Panels 1-8 Found to the East

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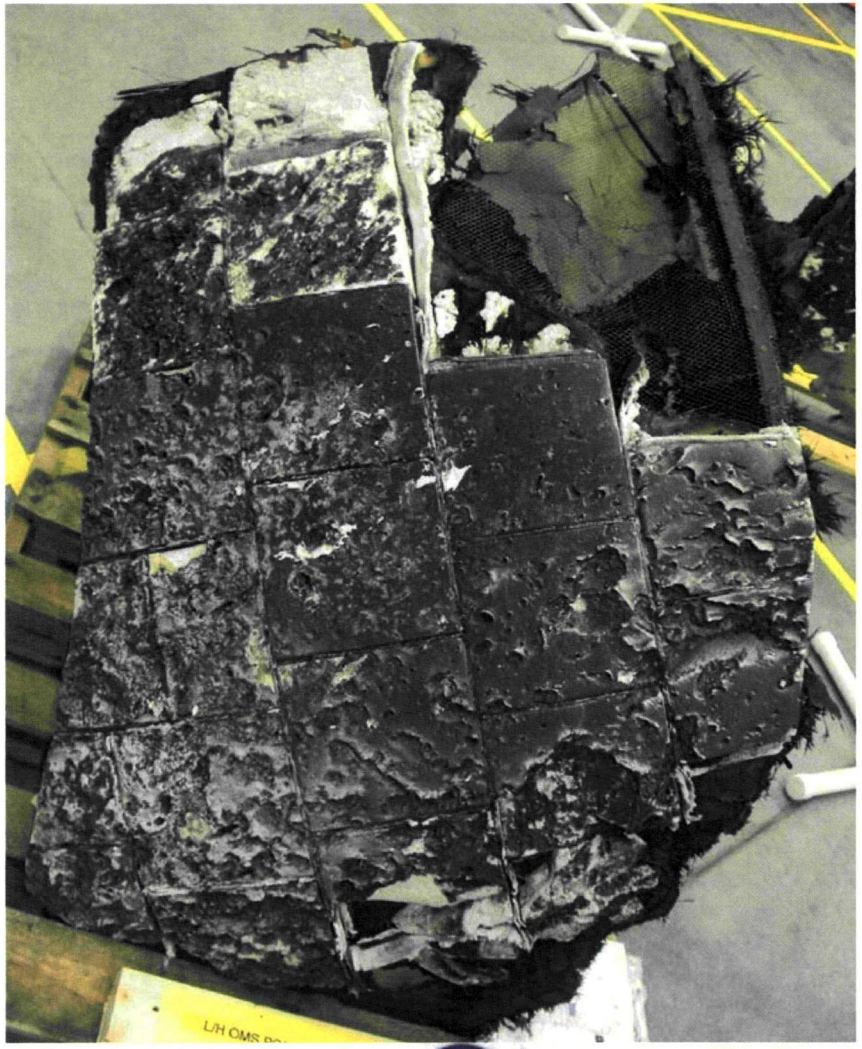
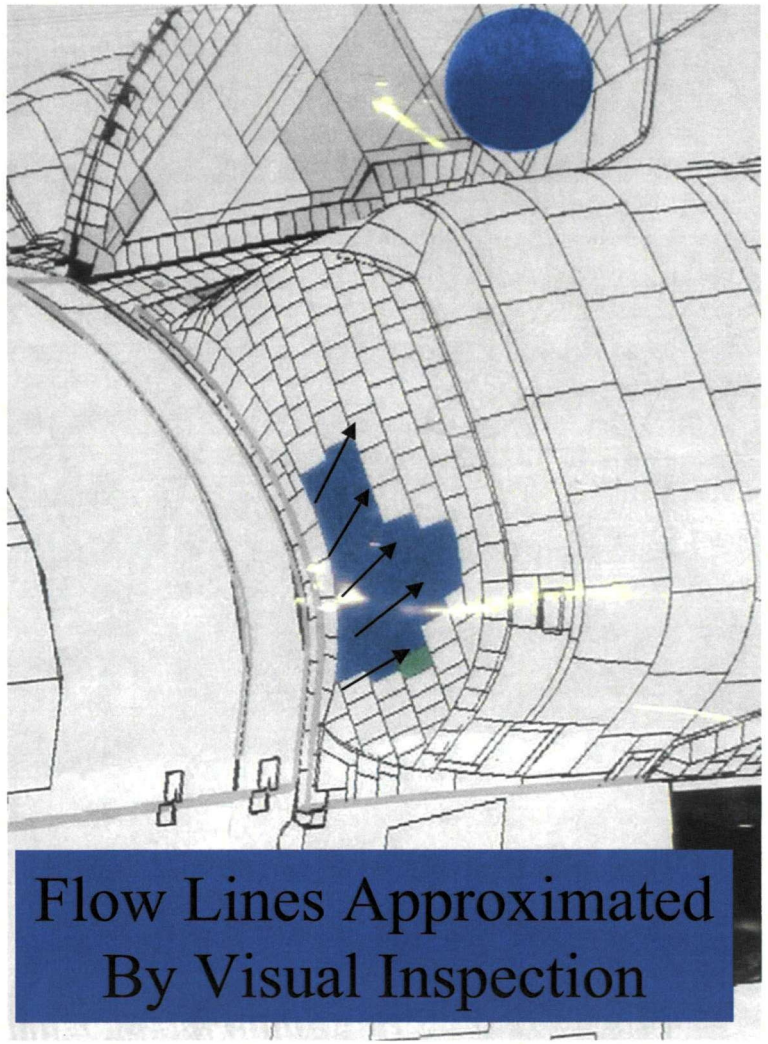
Corroborating Information – LH OMS Pod Analysis





Flow Lines Approximated By Visual Inspection

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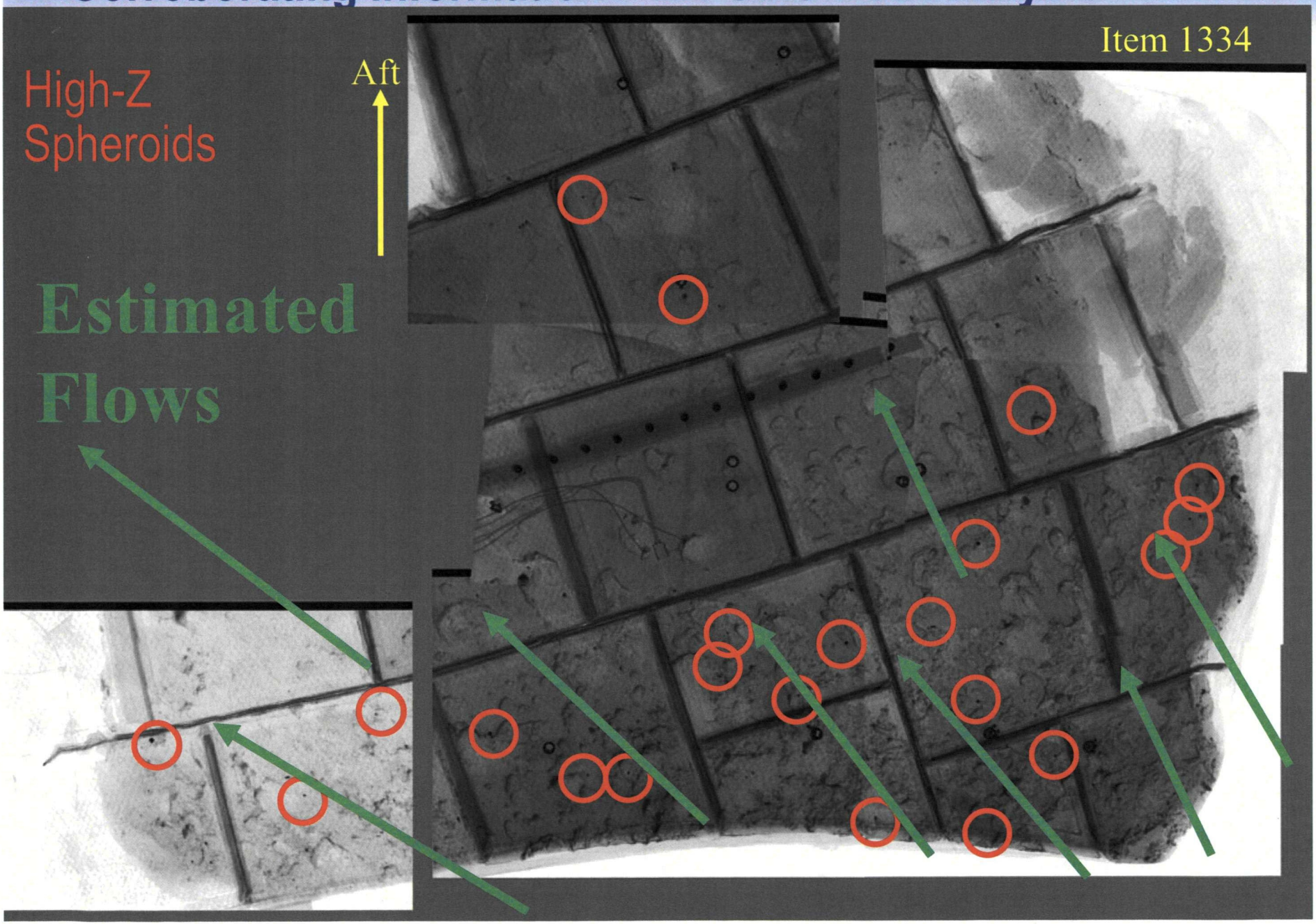
Corroborating Information – LH OMS Pod Analysis



Overall Forensic Conclusions

- Overall forensic assessment is consistent with M&P Team conclusions
- All forensic evidence suggests a breach occurred on the lower surface of the LH RCC panel 8, close to the T-seal with panel 9
- The breach was present early during reentry allowing the ingestion of hot gasses into the wing leading edge cavity, which continued for several minutes prior to vehicle breakup
- Sequence of events:
  - Melting and vaporizing the Inconel 601 foil-covered cerachrome insulation blankets
  - Slumping the wing carrier panel tile immediately aft of the breach
  - Eroding the RCC adjacent to, and downstream of, the breach
  - Melting and/or weakening the Inconel 718 and A286 leading edge attach hardware
  - Destroying the nearby instrumentation and wire bundles
  - Penetrating the aluminum wing leading edge spar

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Conclusions

- The hot gasses, having flooded the wing interior, quickly heated the upper and lower wing surfaces allowing the aluminum honeycomb facesheets and the wing tiles to debond. The thin-wall aluminum truss tubes would soon collapse and the aerodynamic and structural integrity of the left wing would be effectively destroyed
- The forensic evidence is consistent with the observed External Tank foam impact 81 seconds into launch. This is the most probable cause of the damage to the RCC leading edge.

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